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A COST-LOSS RATIO MODEL FOR HURRICANE SORTIE DECISIONS

by

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Lieutenant , United States Navy
B.A., Cornell University, 1986

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

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ABSTRACT

This thesis examines, using the framework of a cost-loss ratio, the dilemma of the Navy decision maker faced with the question of whether or not to sortie ocean-going ships from a port threatened by a hurricane. The long leadtime needed to execute a full sortie requires the decision maker to rely on hurricane forecasts that may contain large errors, despite improvements in forecasting over the past two decades. Furthermore, decision makers may have difficulty interpreting forecasts without the use of a decision aid. Analysis includes interviews with several tropical cyclone experts, a literature review of the economics of hurricanes, and a critique of a number of hurricane decision aids. Based upon this research, this thesis concludes that the CHARM model for setting hurricane readiness conditions is currently the best decision aid available for reducing the number of unnecessary sorties without putting the fleet at significantly increased risk.

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EXECUTIVE SUMMARY

This thesis examines the dilemma of the Navy decision maker who must decide whether or not to sortie ocean-going ships from a port threatened by a hurricane. In his analysis, the decision maker must weigh the large errors in the tropical cyclone forecast. Sortie preparations may be initiated as early as three days in advance of the hurricane's expected landfall; the average 72-hour track forecast error is 309 n mi. Because tropical cyclone forecast accuracy improves as the forecast period decreases, the decision maker may be tempted to put off the sortie decision until more reliable forecasts are available. There is a tradeoff for delaying. If the decision maker waits too long, the rapidly deteriorating weather conditions may prevent a safe departure from the port.

Using the tools of decision analysis, the hurricane sortie problem is modeled as a "game against nature" in which the probability of experiencing destructive winds is compared to the cost of protection divided by the cost of damages incurred when protective measures are not taken. This cost-loss ratio is the critical value above which protection is the optimal course of action and below which it is not. Based on the relative costs, the decision maker should be willing to accept a certain number of unnecessary sorties in order to avoid catastrophic loss. Past attempts to approximate this cost-loss ratio for hurricanes are reviewed. These studies show that, although the cost-loss ratio is a useful criterion for hurricane sortie decisions, huge

variations in the costs associated with hurricane preparations and avoidable damages make the ratio a difficult quantity to estimate directly.

Forecasts used in conjunction with hurricane haven studies provide the decision maker with the raw data needed to make a threat assessment. Nonetheless, he may have difficulty interpreting and integrating all of the information without the assistance of a decision aid. This thesis evaluates how well the existing tropical cyclone decision aids meet the needs of the Navy decision maker facing a hurricane sortie decision. The wind probability forecast is an especially useful tool in that it simultaneously accounts for errors in all aspects of the hurricane: track, translational speed, maximum wind speed and size. There are a number of excellent software packages, such as Automated Tropical Cyclone Forecaster Junior (ATCFjr), Cyclone/Hurricane Acceptable Risk Model (CHARM) and Enhanced GDS, that can help the decision maker visualize and assess the threat to his operations.

The wind probability-based CHARM nomograph for setting hurricane readiness conditions is singled out as the best decision aid available for reducing the number of unnecessary sorties without putting the fleet at significantly increased risk. This model relies on the CHARM concept which proposes that there is some destructive wind level for which preparations must be made and some lower wind level which prohibits most preparations. A CHARM nomograph for a particular location is derived by comparing a

large number of computer-simulated forecasts for hurricanes that passed near the point of interest to hindsight estimates of the actual wind conditions that were experienced. A user-selected confidence level for correctly setting a given readiness condition indirectly estimates the cost-loss ratio threshold values that separate the readiness conditions. This study recommends that CHARM nomographs be developed for harbors used by the U.S. Navy fleet.

Finally, this thesis considers the accuracy of Atlantic tropical cyclone forecasts. The National Hurricane Center official track forecast errors have been steadily decreasing over the past twenty years. Updating the strike and wind probability software to reflect these improvements could lead to considerable savings for the U.S. Navy.

I. INTRODUCTION

A. BACKGROUND

Hurricanes cost the U.S. Navy, on the average, hundreds of thousands of dollars each year in *protection costs* (e.g., costs to secure the base, sortie ships, evacuate aircraft). The Atlantic and Gulf Coasts are threatened by an average of ten tropical cyclones[1] per year (Brand and Blelloch, 1974, p. 353), affecting more than 12 U.S. Navy ports.[2] The average annual cost per military base for hurricane preparedness actions, excluding the costs of unnecessary evasive actions by ships, is estimated as $704,344 in 1993 dollars (National Hurricane Center unpublished cost study, 1993). The Naval Atlantic Meteorology and Oceanography Center (NAVLANTMETOCCEN), Norfolk estimated the cost to sortie 15 ships and eight submarines as $690,000 in 1993 dollars. (NAVLANTMETOCCEN Norfolk "Hurricane Emily Sortie" brief, 1994)

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[1]A *tropical cyclone* is a nonfrontal low-pressure system of synoptic scale developing over tropical or subtropical waters and having a definite organized circulation. A *tropical depression* is a tropical cyclone in which the maximum sustained surface wind is ≤ 33 knots. A *tropical storm* is a warm-core tropical cyclone in which the maximum sustained surface wind is between 34 and 63 knots. A warm-core tropical cyclone in which the maximum sustained surface wind is ≥ 64 knots is called a *hurricane* in the North Atlantic and eastern North Pacific and a *typhoon* in the western North Pacific. (Kotsch and Henderson, 1984, p. 15)

[2]There are 12 U.S. Navy installations in the western North Atlantic and Gulf of Mexico which are serviced by U.S. Navy Strike and Wind Probability Forecasts. The <u>Hurricane Havens Handbook for the North Atlantic Ocean</u> covers these 12 plus 10 additional harbors which may be used by Navy ships. (Turpin and Brand, 1982, p. I-15)

1. The Decision

When faced with the question of whether or not to sortie ocean-going ships from ports threatened by a hurricane, the decision maker must weigh the large errors in the tropical cyclone forecast and assess the relative risks of remaining in port or putting to sea. Each "leave/stay" decision depends on the circumstances of the threat, the operational environment, the characteristics of the port and the capabilities of the vessel. (Turpin and Brand, 1982, I-1)

Unfortunately, ships must initiate preparations for a hurricane sortie well before any hurricane *watches* are issued; likewise, hurricane *warnings* come too late to help with the actual order to sortie.[3] Despite the fact that forecast errors increase as the forecast period lengthens (Neumann and Pelissier, 1981, p. 1264), Navy decision makers are strongly urged to resolve the leave/stay dilemma at an early stage in the threat situation (Commander

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[3]A hurricane watch is a preliminary alert that a hurricane may threaten a specified portion of the coast. A watch typically is issued 36 hours before landfall could occur. A hurricane warning indicates that hurricane conditions are expected within 24 hours along a specified portion of the coast. (Turpin and Brand, 1982, I-12) During the 1970s, hurricane warnings were issued, on the average, 19 hours prior to landfall. According to Neumann and Pelissier (1981),

> ...the time of issuance of hurricane warnings represents a compromise between an effort to minimize the area of overwarning and an attempt to provide enough lead time in which to complete precautionary actions....Experience has shown that, in most cases, an effective compromise is achieved if warnings are issued about 18 hours before landfall, 12 hours of which occur during daylight.(Neumann and Pelissier, 1981, pp. 1264-1265).

The area damaged by a hurricane typically encompasses one-third of the warned area, therefore approximately two-thirds of the area protects unnecessarily and is, in effect, "overwarned" (American Meteorological Society, 1993, p. 1377).

in Chief U.S. Atlantic Fleet Letter, 13 April 1982). The tradeoff for delaying the decision until more accurate forecasts are available is the possible elimination of the sortie as a viable option due to the rapidly deteriorating weather conditions. Consequently, there exists an optimal decision point where the marginal benefit of improved forecast accuracy equals the marginal cost of decreased safety.

In his analysis, the decision maker should also balance the cost of protection against the cost of avoidable damages. In the past, it has been assumed that if one sorties unnecessarily nine out of ten times, it will still be cost effective (Interview between Charlie Mauck, Fleet Numerical Meteorology and Oceanography Center, Monterey and the author, 13 May 1994). This implies a ratio of costs to losses of 10%. However, it is difficult to come up with one ratio that accounts for all ships and all hurricanes (see Chapter III). Damage and preparation costs can vary greatly; when astronomical losses occur, this ratio approaches zero. For example, the USS Regulus ran aground in the Hong Kong harbor after the passage of Typhoon Rose in August 1971, costing the U.S. Navy approximately $8-10 million in 1971 dollars (Brand and Blelloch, 1974, p. 354).[4] Using the cost estimates from Brand and Blelloch (1971) for fuel, pilot and tug fees, boat transportation, "lighting off" the boilers, and overtime for the civilian charter

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[4]Pacific typhoons are typically larger and stronger than Atlantic hurricanes and therefore cause more damage.

crew, the cost for a two-day sortie for a chartered cargo ship can be estimated as $20,000 in 1971 dollars. Taking the cost of damage as $10 million, the resulting *cost-loss ratio* is .002. This means that it is worthwhile to sortie 500 times unnecessarily to avoid the damage caused by one mishap of the magnitude suffered by the USS Regulus!

Another issue that will affect the hurricane sortie decision is the decision maker's attitude toward risk. Given the extremely high costs incurred if protective measures are not taken and the hurricane hits, there is a natural inclination to choose a conservative course of action. Protection costs are certainly less visible than the losses suffered if ships "get beat up pierside." (Telephone conversation between CDR Lilly, NAVLANTMETOCCEN Norfolk and the author, 9 May 1994) Few Naval officers can afford to make career-impacting mistakes like that, regardless of how well-informed the decision. Chapters II and V discuss further the concept of risk.

The sortie decision will also depend on how the decision maker interprets the forecasts. At the time that the decision maker must make the call, the probabilities may still be quite low. However, it is not uncommon for a decision maker to automatically assume that the hurricane is heading straight for his area of responsibility and thus perceive the probability of being "hit" as being much larger than it is. This phenomenon is known as the *base effect*. Conversely, the decision maker may be reluctant to order

a sortie based on such a low probability. Because "major hurricanes are infrequent events for any given location," (Sheets, 1990, p. 189) the decision maker may have never experienced the full force of a major hurricane and consequently may underestimate the seriousness of the threat.

2. The Decision Makers

Responsibility for tropical cyclone forecasting and for issuing hurricane watches and warnings in the North Atlantic and the eastern North Pacific rests with the National Hurricane Center (NHC), one of three national centers operated by the National Weather Service (NWS). The NHC also conducts a post-storm analysis to determine the best estimate of the actual track of a storm.(Sheets, 1990, p. 186)

For the U.S. Navy, the Base Commander is responsible for setting hurricane *conditions of readiness*[5], opening and manning shelters and securing base personnel. The Senior Officer Present Afloat is responsible for sortie decisions. (COMNAVBASENORVA/SOPA(ADMIN)HAMPINST 3141.1S, 18 May 1993, p.4) The NAVLANTMETOCCEN Norfolk makes sortie recommendations and recommendations regarding setting readiness conditions; it also issues Navy tropical cyclone warnings that essentially

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[5]Hurricane conditions of readiness are defined as follows:
Condition IV: hurricane force winds (≥ 64 kts) are possible within 72 hours.
Condition III: hurricane force winds (≥ 64 kts) are possible within 48 hours.
Condition II: hurricane force winds (≥ 64 kts) are anticipated within 24 hours.
Condition I: hurricane force winds (≥ 64 kts) are anticipated within 12 hours.

reproduce the NHC warnings (Telephone conversation between CDR Lilly, Operations Officer, NAVLANTMETOCCEN, Norfolk and the author, 9 May 1994).

B. IMPORTANCE OF THE STUDY

In the past, the U.S. Navy has sent its decision makers mixed messages about hurricane decision aids. For example, the Navy contracted the development of a decision model for setting hurricane readiness conditions (the Cyclone/Hurricane Acceptable Risk Model), but omitted its inclusion in official policy documents such as the Hurricane Havens Handbook for the North Atlantic Ocean (Turpin and Brand, 1982). These inconsistencies may be attributed to the confusion of decision *aiding* with decision *making*, and the perception of the models as unreliable. Some people have a basic mistrust of rational, prescriptive models, perhaps fearing that the rational model will be followed blindly and without consideration of its limitations. The Hurricane Havens Handbook for the North Atlantic Ocean amplifies on this idea:

> Objective methods for setting Hurricane Conditions on the basis of the forecast "open ocean" winds would have supported many unnecessary sorties as a result of ignoring the effects of increased friction on the surface wind field....The penalty for abandoning a well-rounded evaluation of each hurricane threat in favor of a purely "objective" approach based upon certain probabilities of strike and 50-kt winds will be a large increase in unnecessary sorties. Instead, a current tropical cyclone threat should be monitored with the best

objective aids available, but also with a keen awareness of the character of the "worst case" threat and the likely impact of lesser threats."[6] (Turpin and Brand, 1982, I-5)

Slovic (1984), on the other hand, levies a strong argument in favor of the rational model:

> In the face of uncertainty, man may be an intellectual cripple whose intuitive judgements and decisions violate many of the fundamental principles of optimal behaviour. These intellectual deficiencies underscore the need for *decision-aiding techniques*. (Singleton and Hovden, p. 151, italics added)

← Ref is not included in Bibliography!

According to Baird (1989), "The era of the successful intuitive decision maker is over."(Baird, 1989, p. xi)

Despite the U.S. Navy's cautiousness about using objective methods for assessing hurricane threats, it continues to fund the development of tropical cyclone decision aids. A CINCPACFLT requirement states as its objectives:

> Develop forecasting decision aids for tropical cyclones and assess forecast content. Evaluate the reality of the 135 nm statistical error buffer added to the 30 kt wind forecast zone; identify applicable, newly-developed algorithms and decision aids such as the charm [sic] model decision criteria; identify, if necessary, new decision aid algorithms which will assist commanding officers to determine optimum operational tactics and acceptable levels of risk for both personnel and material when under the threat of heavy weather. (COMNAVOCEANCOM PAC MET 87-07, 1991)

[6] Actually, Brand was an advocate of adding just such a probability-based decision model to each port evaluation. (Interview between Sam Brand, Naval Research Laboratory Monterey and the author, 6 May 1994)

The apparent mistrust of rational models is fueled, in this case, by the inadequacies of the existing decision aids and the errors in the model inputs, the tropical cyclone forecasts. The following case study highlights the need for improved hurricane decision aids and forecasts. In 1993, Norfolk Naval activities were threatened by Hurricane Emily. The decision was made to conduct a partial sortie despite a recommendation to the contrary from the NAVLANTMETOCCEN Norfolk.[7] After Hurricane Emily recurved to the north, missing Norfolk, the NAVLANTMETOCCEN Norfolk performed a cost analysis which was briefed at the 1994 Interdepartmental Hurricane Conference. The results of the cost analysis are given in Chapter III. The purpose of the brief was to emphasize the special requirements of Naval stations as customers of the National Hurricane Center's forecasting and advisory services. The NAVLANTMETOCCEN Norfolk expressed a desire for significantly improved forecast accuracy out to 72 hours (specifically, a two-thirds reduction in forecast error), forecasts extended out to 96 hours in order to have sufficient lead time to sortie the ships in port, and improved basin-specific storm surge models.(NAVLANTMETOCCEN Norfolk "Hurricane Emily Sortie" brief, 1994) According to CDR Lilly, Operations Officer, NAVLANTMETOCCEN Norfolk, three tools were used to analyze

[7]According to Mr. Dixon, Ship Routing Officer, NAVLANTMETOCCEN Norfolk, even though the admirals overrode the oceanographers' recommendation and an unnecessary sortie was conducted, "Everyone came out looking good." (Telephone conversation between Pat Dixon, NAVLANTMETOCCEN Norfolk and the author, 10 May 1994)

the threat: the Hurricane Havens Handbook for the North Atlantic Ocean, Automated Tropical Cyclone Forecasting Junior (ATCFjr) and GDS. These decision aids are reviewed in Chapter IV. The most influential input came from discussions on the NWS Hurricane Hotline (Sheets, 1990, p. 210) which is used for a conference call involving a National Meteorological Center forecaster, forecasters at local National Weather Service offices that might be affected, and the National Hurricane Center hurricane specialist. Surprisingly, CDR Lilly said that the command never received the U.S Navy Strike and Wind Probability messages. (Telephone conversation between CDR Lilly, NAVLANTMETOCCEN, Norfolk and the author, 9 May 1994)

C. PROBLEM STATEMENT

Although forecasting ability is steadily improving (see Chapter VI), forecast errors have not diminished to the point where they can be ignored. Lack of forecast accuracy is only part of the problem. A forecast methodology has evolved that is oriented more toward the mentality of the forecaster rather than the decision maker. The decision maker wants to know "when, where and how badly will it affect me?" and he wants to know in time to act on the information. The current forecast system provides this information marginally or not at all beyond the 18-24 hour forecast period.

Brand (1992) believes that progress is already being made in this area: "Over the past decade, there has been a shift in emphasis from the purely environmental toward applied uses of meteorological data to aid the Navy decision maker in tactical decision-making applications." (Brand, 1992, p. 32)

Forecasts need to be repackaged into a simple, user-friendly form so that a decision maker can quickly assess the threat. This thesis will examine how well the existing hurricane decision aids meet the needs of the Navy decision maker facing a hurricane sortie decision for ships.[8]

D. RESEARCH METHODOLOGY

Research methodology includes an extensive literature review covering the following pertinent topics: decision analysis, risk, hurricane decision aids, disaster preparedness, cost effectiveness of weather forecasting, and the estimation of hurricane costs. Interviews were conducted with Sam Brand, Naval Research Laboratory, Monterey; Jerry Jarrell, National Hurricane Center, Miami; Charles Neumann, Science Applications International Corporation, Miami; Russell Elsberry, Naval Postgraduate School, Monterey; Mary Clifford and Charlie Mauck, Fleet Numerical Meteorology and Oceanography Center, Monterey; CDR

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[8]Aircraft evacuation also presents a problem to the Navy decision maker. Although aircraft sorties require a shorter lead time than ship sorties, a lower wind criterion is used for aircraft sortie decisions. This thesis will focus mainly on ship sorties.

Manthey, Naval Safety Center, Norfolk; and CDR Lilly and Pat Dixon, Naval Atlantic Meteorology and Oceanography Center, Norfolk.

E. ORGANIZATION OF THESIS

Drawing from decision theory, risk analysis and utility theory, Chapter II of this thesis defines the role that each of these disciplines plays in the hurricane sortie decision. Chapter III summarizes the research on hurricane damage and preparation costs. Chapter IV reviews alternative decision aids for assessing hurricane threats. Chapter V presents the CHARM nomograph for setting hurricane conditions of readiness as the primary decision model for resolving protect/do not protect dilemmas. Chapter VI discusses the accuracy of Atlantic tropical cyclone forecasts. Chapter VII provides recommendations for improving existing decision aids and incorporating new ones. Possible areas for future research are suggested.

II. CONCEPTUAL FOUNDATIONS OF THE STUDY

A. INTRODUCTION

This chapter establishes the conceptual foundation for the remainder of the thesis. The elements of decision analysis and the structuring of these elements in the form of influence diagrams, decision trees and contingency tables are presented as a framework for investigating the hurricane sortie dilemma. The basic cost-loss ratio situation is introduced as the traditional means of modeling the protect/do not protect problem, and decision criteria for selecting the optimal course of action are considered. The chapter ends with a discussion of the errors that can result from decision making under uncertainty.

B. ELEMENTS OF DECISION ANALYSIS

Decision analysis imposes logical structure on the reasoning that underlies decision making. According to Corner and Kirkwood (1991),

> Decision analysis provides tools for quantitatively analyzing decisions with uncertainty and/or multiple conflicting objectives. These tools are especially useful when there is limited, directly relevant data so that expert judgment plays a significant role in the decision making process.(Marshall and Oliver, 1994, p. 3)

Decision analysis entails the consideration of five elements: actions, events, probabilities, consequences and utilities (Winkler and Murphy, 1985, p. 494). Each of these elements will be defined for the hurricane sortie decision.

1. Actions

The first element is a set of courses of action. There is no decision unless a choice is to be made among possible alternatives. It is important that the decision maker consider all the options before paring down the list for the purpose of modeling. Some potential courses of action in the face of an approaching hurricane are: conduct a full sortie of all ships in port, conduct a partial sortie[9], or do nothing (wait for more accurate forecast). In the typical model of the hurricane sortie problem, the decision maker selects from only two courses of action: protect (P) and do not protect (P'). In Chapter V, P and P' denote "start to prepare" and "do not start to prepare", respectively. These actions refer to the preparations associated with setting hurricane readiness conditions.

2. Events

The consequence experienced by the decision maker depends not only on the action taken, but on the outcome of one or more random events.

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[9]Ship size is usually the determining factor when deciding which ships to sortie. Ships with large sail areas (generally larger than frigate size) tend to drag anchor and therefore should evade at sea.(Turpin and Brand, 1982, p. II-1)

Also known as states or variables, events are possible occurrences which are partly or completely outside the decision maker's direct control (Barclay, et al., 1977, p. 3). For the hurricane sortie problem, a whole range of variables relating to the ship, the harbor and the hurricane are relevant:

a. Ship Variables

1) the ship's ability to maneuver and gain a favorable position relative to the hurricane if the ship must get underway (i.e., power and drag factors under adverse conditions);

2) the ship's ability to withstand adverse weather conditions while moored, anchored, alongside or in dock;

3) fuel availability.

b. Harbor Variables

1) holding quality;

2) maneuvering room;

3) support and repair facilities (normal and emergency);

4) port congestion;

5) quality of moorings and piers under adverse conditions.

c. Environmental Variables

1) forecast track of the hurricane relative to the port;

2) forecast intensity, translation speed, and wind distribution of the hurricane;

3) topography of the surrounding terrain and the resulting influence on the harbor;

4) forecast storm surges, sea states and tides. (Brand, 1978, p. 374).

Most hurricane decision models narrow the focus to two events: adverse weather is experienced (W) and adverse weather is not experienced (W'). In Chapter V, adverse weather is interpreted as the presence of destructive winds (≥ 50 kts).

3. Probability Forecasts

The decision maker will want to obtain information or forecasts about how likely it is that a particular act will result in each of the consequences. The uncertainty regarding the event outcomes can be represented formally by probabilities; of primary interest for the hurricane sortie decision are strike and wind probability forecasts (see Chapter IV).

Murphy (1977) showed that, when the forecasts are reliable, the value associated with probabilistic forecasts is greater than or equal to the value associated with climatological and categorical forecasts for all activities (Murphy, 1977, p. 815). For example, it is more helpful to know that the probability of rain is 0.20 than it is to be told that, based on historical data, Monterey has a 25% chance of getting rain on this date or to be told simply

that it will or will not rain today. The reliability of probability forecasts is addressed in Chapter VI.

4. Consequences

The decision maker must also consider the possible consequences of each action. For the hurricane sortie decision, if the decision maker fails to protect and adverse weather does not occur, no cost is incurred and no damage is suffered; the monetary consequence is zero. Failing to protect when adverse weather does occur causes damage in the amount L. In the simplest case, protection is 100% effective, but costs an amount C, whether adverse weather is received or not. It is assumed that $0 \le C \le L$; otherwise, the dominant strategy would be to never protect.

The consequences themselves may be stochastic. Murphy and Ye (1990) described a time-dependent situation in which a decision maker contemplates postponing the protect/do not protect decision in anticipation of obtaining more accurate forecasts at some later time, but also recognizes that the cost of protection will increase as lead time decreases (Murphy and Ye, 1990, pp. 939-940). For the Navy decision maker, the penalty for delaying may take the form of a smaller set of feasible actions rather than higher protection costs. In Chapter V, the consequences experienced when the decision is made to protect are a function of the probability of 30-kt winds.

There are serious consequences of hurricane sortie decisions (i.e., loss of life, decreased crew morale, cancelled fleet exercises and decreased national security due to reduced readiness of military bases) which cannot be expressed in monetary terms. These consequences factor into the decision-making process, but will not be explored in this thesis.

The Navy decision maker may experience individual or personal consequences as a result of the action taken. The Navy policy is clear:

> Prudent, early action by commanders and commanding officers in response to tropical warnings is essential. Deviation from standard and recommended hurricane evasion tactics can be justified only by extreme operational necessity. Fleet capabilities must not be degraded due to casualties resulting from tropical storms and hurricanes. (CINCLANTFLT Letter dated 13 April 1982)

If a decision is made to protect and the base subsequently receives hurricane-force winds, the decision maker may be commended for having chosen wisely. However, since protecting is the standard operating procedure, the decision maker might be viewed as just having done his job. If the hurricane misses the base, the dollars spent on the unnecessary sortie would probably be considered a cost of doing business, no real loss to the Navy. Chapter III addresses whether or not this attitude is justified.

If, on the other hand, the Navy decision maker does not order a sortie and disaster strikes, the decision maker may lose his career. If the decision maker correctly interprets the threat as innocuous and opts to do nothing, he invites criticism for risking the fleet. In this case, the decision maker is

not rewarded for saving the Navy the cost of protection, thus there is no incentive for the decision maker to even assess the threat; the optimal decision is to protect.

These individual consequences illustrate the need to incorporate in the analysis the decision maker's preferences. Preferences are traditionally measured in terms of utilities, which will be addressed in the next section.

5. Utilities

The last element in the decision analysis process is concerned with how attractive or unattractive each possible consequence is to the decision maker. This subjective measure of value is called utility. Utilities reflect the decision maker's attitude toward risk. Three general types of utility functions can be distinguished and are shown in Figure 1.[10] (Moskowitz and Wright, 1979, p. 160)

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[10]Individuals may not exhibit the same attitude toward risk under all circumstances, thus defying neat categorization. For example, a normally risk aversive person may purchase a lottery ticket every Saturday.

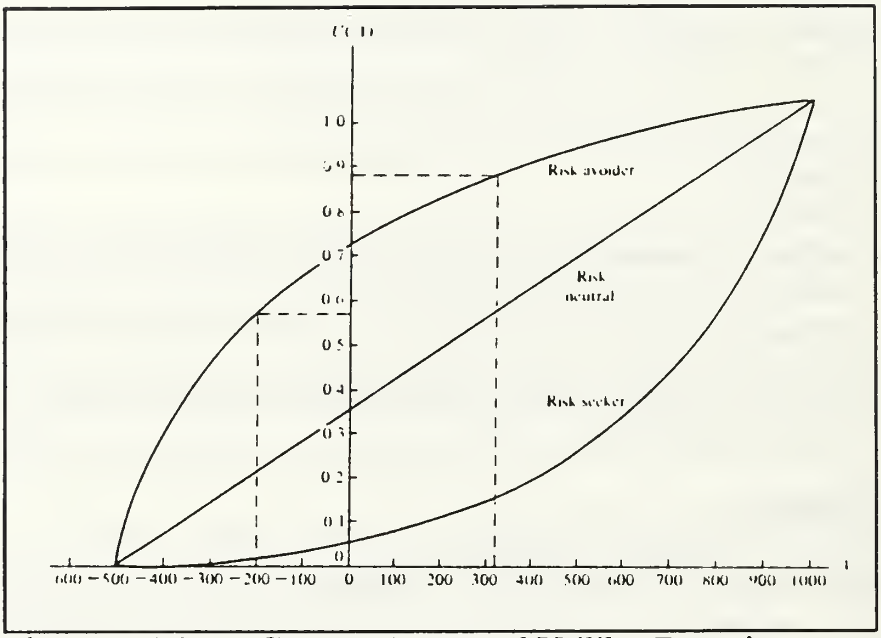

Figure 1. Three General Types of Utililty Functions. (from Moskowitz and Wright, 1979)

A concave-downward shape is characteristic of the utility curve for a risk-averse individual who has a diminishing marginal utility for money. For the risk averse, an additional dollar has less value than the last one gained, therefore, a 50/50 chance of winning or losing a dollar will be unattractive. The risk avoider ". . . will feel the loss of a dollar that he already has with a pain that will exceed the pleasure to be gained from winning an additional one." (Douglas, 1983, p. 43) The risk-averse person buys insurance, preferring a certain small loss to avert the small chance of a large loss.

A linear function depicts the behavior of a person who is "neutral" to risk. A risk-neutral individual is indifferent to an even bet and places the same amount of value on the first dollar earned as on the last. For the risk

neutral, maximizing expected utility is equivalent to maximizing expected monetary value. For this reason, the linear model is frequently used.

The risk seeker's utility curve is concave-up, with the slope of the utility curve increasing as the dollar amount increases. This type of person willingly accepts gambles (risky ventures) that have a smaller expected value than an alternative payoff received with certainty (riskless alternative). For this risk-prone individual, the attractiveness of a possibly large payoff in the gamble far outweighs the fact that the probability of such a payoff may be exceedingly small. Chapter V provides interesting illumination on utility theory in the area of losses.

C. STRUCTURES

The elements of decision analysis can be organized into influence diagrams, decision trees and contingency tables. These structures can assist in the solution of complex decision problems. Figure 2 depicts an influence diagram for a situation in which a forecast or expert opinion is solicited in order to improve the prediction of outcomes and reduce uncertainties (Marshall and Oliver, 1994, pp. 271).

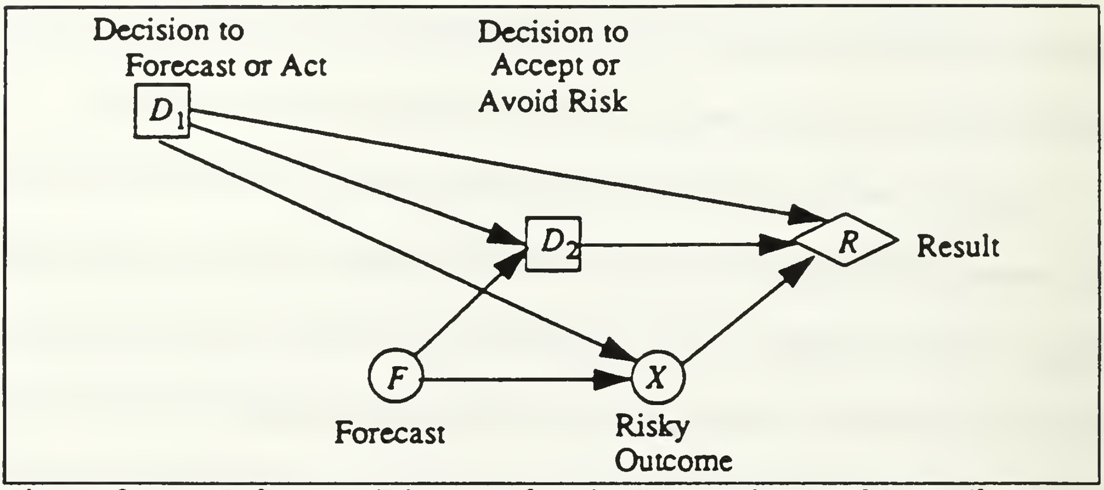

Figure 2. An Influence Diagram for the Protection Problem. (from Marshall and Oliver, 1994)

The decision, event and result nodes are laid out from left to right, in the order of occurrence. An initial decision D_1 must be selected from the decision set D_1 = {RA, RV, Forecast}, where RA represents choosing the riskless alternative (P) and RV represents choosing the risky venture (P') If RA is chosen, then result r_2 (C) is obtained. Selecting RV could result in either r_1 (L) or r_3 (0), depending on the outcome of X. The random outcome set X = {1 if it is a hurricane (W), 0 if it is not a hurricane (W')}. If either RA or RV are chosen, then a second decision need not be considered. If Forecast is chosen, then the forecast outcome F must be observed before a second decision D_2 is selected from the set D_2 = {RA, RV}; again, RA results in r_2, whereas RV could result in r_1 or r_3. (Marshall and Oliver, 1994, pp. 270-271)

The directed arcs from D_1 and F to D_2 indicate that both D_1 and F are known to the decision maker before D_2 is made and that their values may

influence D_2. The arc from D_1 to X indicates that the distribution of X depends on the initial decision made. The arc from F to X implies that the forecast and the event being forecast are related and that the distribution of F is known when the distribution of X is being assessed. The three arcs leading into R show that the result depends on both decisions and on the random event, X. (Marshall and Oliver, 1994, p. 271)

The corresponding decision tree is given in Figure 3, where p_X is the climatological probability, p_F is the probability that the forecast will say it is a hurricane, p_1 is the probability that it is a hurricane, given that the forecast said it is a hurricane, and p_0 is the probability that it is a hurricane, given that the forecast said it is not a hurricane. As discussed previously, $0 \leq C \leq L$. (Marshall and Oliver, 1994, p. 272)

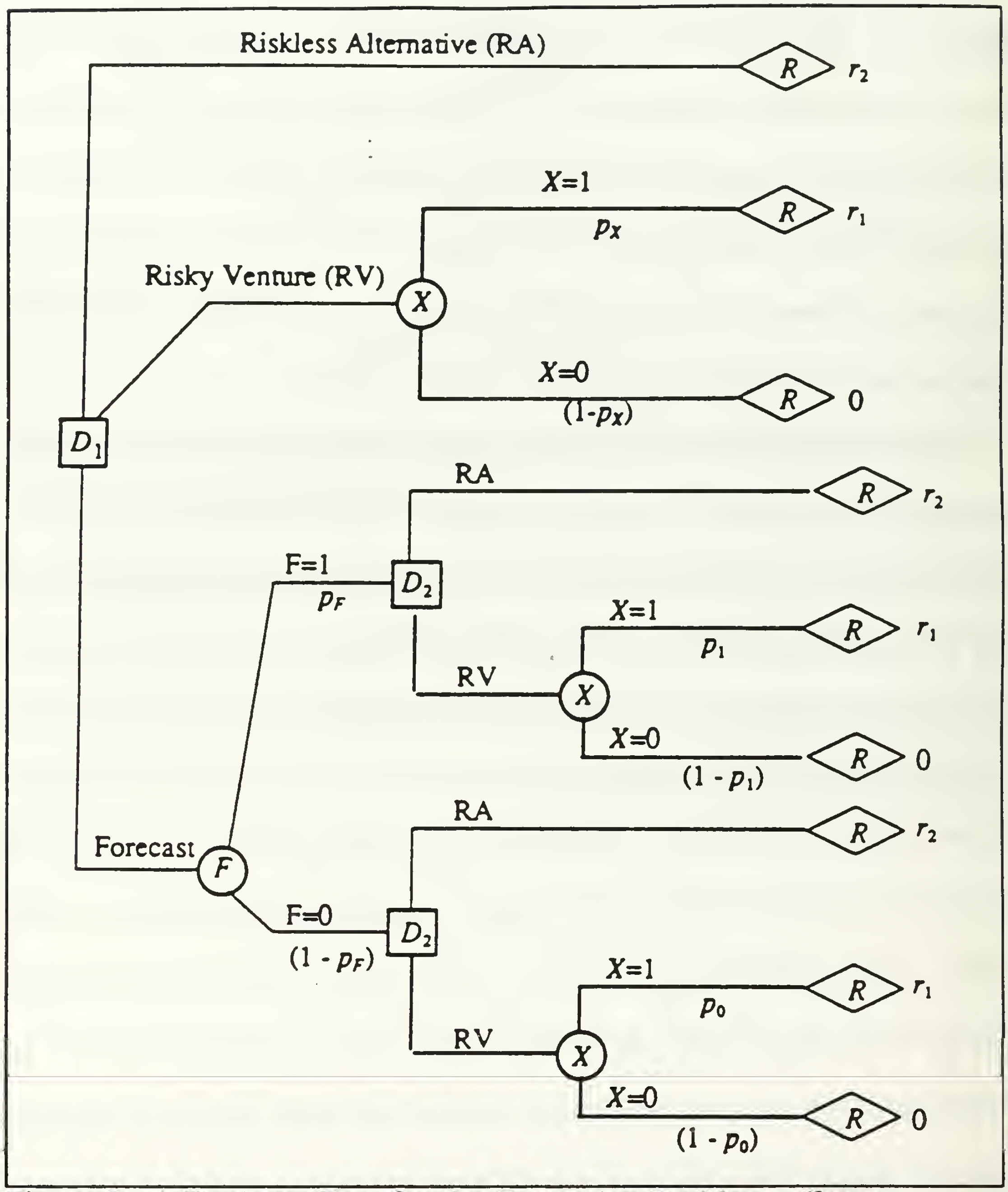

Figure 3. A Decision Tree for the Protection Problem. (from Marshall and Oliver, 1994)

An alternative format is the contingency table. Other names for this format are payoff matrix, game box, cost table, cost matrix, outcome table and utility table, depending on what is put in the cells. Figure 4 is an

example of a cost matrix where each cell contains the resultant cost associated with each combination of event and action.

		Event	
		W	W '
Action	P	C	C
	P '	L	O

Figure 4. A Cost Table for the Protection Problem. (after Winkler and Murphy, 1985)

This is the structure that is used in Chapter V to illustrate the derivation of the curves in the CHARM model. The table format is also used to report the CHARM model results; however, the numbers in each cell will represent frequencies, not costs. The next section will examine the hurricane problem within the context of the cost-loss ratio situation and discuss the solution of the problem using different decision criteria.

D. THE COST-LOSS RATIO SITUATION

The hurricane sortie problem has most frequently been viewed as a *cost-loss ratio situation* (Thompson, 1952) in which a decision maker must decide ". . . whether or not to protect an activity or operation against adverse weather in the face of uncertainty as to whether or not such weather

conditions will actually occur." (Murphy and Ye, 1990, p. 939) In this "game against nature", it is assumed that the decision maker will try to select the activity that will yield the lowest expected losses, regardless of the weather outcome.[11] Thompson and Brier (1955) showed that, for a continuing series of repetitive operations, the optimum long-run economic gain will be realized if protective measures are taken if $P > C/L$, where P is the probability of adverse weather, C is the cost of taking protective measures on a single occasion and L is the loss suffered on each occasion that adverse weather occurs and protective measures have not been taken. Similarly, protective measures should not be taken if $P < C/L$. The decision maker will be indifferent between the two actions when $P = C/L$. The value C/L therefore represents a critical ratio (sometimes referred to as a cost-benefit ratio), above which protection is the optimal course of action and below which it is not. (Thompson and Brier, 1955, p. 250) Subsequent studies involving the cost-loss ratio situation have been undertaken by Nelson and Winter (1960), Thompson (1962), Shorr (1966), Anderson and Burnham (1973), Murphy (1977), Jarrell and Brand (1981), Winkler and Murphy (1985), Murphy and Ye (1990) and others.[12]

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[11]Recall that this assumption is equivalent to assuming that the decision maker's utilities are linearly related to the expenses. This model also assumes a rational decision maker.

[12]Not everyone agrees that the cost-loss ratio is a good decision criterion. In fact, in a lecture on measuring the values of action alternatives using "social utilities," Ward Edwards (1971) emphasized that the "knapsack" problem (a special optimization problem where there is a budget constraint) "is the *only* case ... in which the famous benefit-to-cost ratio

Several non-probabilistic decision criteria have been developed for individuals who may prefer not to use probabilities in their analyses. The maximin payoff, the minimax payoff, the maximax payoff and the minimax regret will be discussed briefly in terms of the hurricane sortie decision (refer to Figure 4).

Maximin is the criterion of pessimism. Under this principle, the decision maker assumes that once he has chosen a course of action, nature or the system will be malevolent and select the event that minimizes the decision maker's payoff.[13] The decision maker, therefore, should pick the best of the worst and always protect. (Buck, 1989, p.35) Likewise, a decision maker using a *minimax* strategy (minimizing the maximum payoff) will choose to always protect.

Maximax, on the other hand, is an extremely optimistic criterion. Here the decision maker considers the largest payoff (best outcome) for each action over all possible events and, of these, chooses the course of action for which the payoff is the largest. For the cost-loss ratio situation, the best outcomes are C for P and 0 for P', which means that the decision

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is an appropriate figure on which to base a decision." (American Society for Engineering Education, 1980, p. 126) Furthermore, Edwards' approach to decision making ignored probabilities altogether. Pointing out that there is no such thing as a riskless choice in the real world, Edwards rationalized, "If you are uncertain enough, it's the same as though you were certain." As Edwards was quick to admit, these were heretical ideas for 1971 and are not views which have been readily accepted by others in the field today. (American Society for Engineering Education, 1980, p. 120)

[13]"Payoff" refers to a negative cost.

maker should never protect since 0 is preferred to C. (Winkler and Murphy, 1985, p. 500)

In order to use a *minimax regret* criterion, the cost matrix must first be converted into its corresponding regret matrix by subtracting each entry in the cost matrix from the best outcome in its column. Minimax can then be applied to the regret matrix. The decision maker following this rule will protect if $C < (L - C)$ or if $0.5 > C/L$.

E. TYPE I AND TYPE II ERRORS

When conducting a hypothesis test, there are two kinds of errors which can be made, type I and type II. Type I errors result from rejecting the null hypothesis when it is true. Type II errors result from failing to reject the null when it is false. Obviously, it is desirable to keep both type I and type II errors at a minimum.[14] It is possible to eliminate all type I errors by making the rejection region extremely small, but this causes an increase in the probability of a type II error.

This tradeoff can be seen in the hurricane sortie problem. Let the null hypothesis be the status quo, that destructive winds will not affect the military base. The alternate hypothesis, then, is that the base <u>will</u> be hit by destructive winds. A type I error in this case would result in a false alarm:

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[14]The only way to reduce simultaneously the probabilities of both errors occurring is to reduce the variance, which for the hurricane sortie problem means improving forecast accuracy.

protecting (P) when adverse weather is not experienced (W'). A type II error is much more serious: failing to protect (P') and being caught unexpectedly by adverse weather (W). By setting as a goal the elimination of all unnecessary sorties, the probability of incurring ship damage due to adverse weather increases. In the CHARM model, decision makers are allowed to choose confidence levels for correctly setting hurricane readiness conditions (see Chapter V). Although most decision makers would want to be 100% sure that the course of action they are taking is the right one, selecting a confidence level of 100% guarantees higher overwarning rates.[15] (Kostyshack and Jarrell, 1984, p. 13)

Thompson (1952) spoke to the desirability of an optimal balance between type I and type II errors:

> The relative importance of these two kinds of errors depends upon the nature of the operation for which the prediction is used . . . . The usual forecast is aimed at suiting the "average" user, and it is generally considered desirable that the two types of errors be equal . . . (Thompson, 1952, p. 224)

In the hurricane sortie problem, because typically C <<< L, it is preferable to err on the side of caution and accept a few unnecessary sorties in order to reduce the probability of a huge loss. Clearly, the probability of a type I error should far outweigh the probability of a type II error, but to what degree? This is where the cost-loss ratio comes into play. In Chapter III,

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[15]In this context, "overwarning" refers to setting a condition of readiness that later proves to be unwarranted by the weather conditions.

past attempts at quantifying hurricane costs in order to estimate the cost-loss ratio will be reviewed.

III. HURRICANE COSTS

A. INTRODUCTION

This chapter summarizes the results of a literature review of works dealing with the economics of hurricanes. Earlier studies by Harold Demsetz (1962), Arnold Sugg (1966) and Malone and Leimer (1971) are still relevant and provide the basis for later works by Anderson and Burnham (1973), Charles Neumann (1975) and Brand and Blelloch (1975). For each study, a brief synopsis will be given of the research methodology and results as they pertain to preparation costs, hurricane losses, and savings due to improvements in forecasting. Estimates of tropical cyclone damage to Navy vessels while moored or anchored, as well as recent estimates of ship sortie costs will also be reported.

B. HURRICANE COST ESTIMATION STUDIES

1. Demsetz (1962)

In a RAND study, Demsetz (1962) suggested that the annual tropical storm cost for a specific region given **imperfect forecasting** could be computed as the sum of the annual preparation costs, the annual damage costs caused by storms for which prior warning is received, and the annual damage costs caused by storms for which no prior warning is received. Similarly, the annual tropical storm cost given **perfect forecasting** could be

calculated as the number of storm warnings per year multiplied by the sum of the protection cost per storm and the damage cost per storm where prior warning is received. (Demsetz, 1962, pp. 7-9) These costs were estimated for Miami, Florida using records of two storms which struck the Miami area. A tropical storm that occurred on 10 September 1960 provided an example of a storm of moderate intensity for which adequate warning was received. Total private and public preparation costs for this storm in 1962 dollars were estimated as $1.2 million and total damage costs as $6.6 million (Demsetz, 1962, p. 7). Going back in the archives to October 1950, Demsetz found an intense storm for which only short notice was given which he used as the basis for his estimate of the damages caused by an average storm for which no prior warning was received. Again using 1962 dollars, this intense hurricane caused approximately $12.7 million in damages; Demsetz placed the cost of damage caused by an average storm without warning slightly higher at $13 million. (Demsetz, 1962, p. 11)

Finally, the value of forecasting was investigated by comparing Miami's annual storm costs resulting from four different warning systems. The difference between no warning system and a perfect warning system represented the maximum gain that could be expected from forecasting. The annual storm cost, given **no forecasts**, was estimated as $7.54 million in 1962 dollars (.58 storms/year x $13 million). The annual storm cost, given

perfect forecasts, was estimated as $4.51 million in 1962 dollars, for a total savings of about $3 million a year.(Demsetz, 1962, pp. 13-14)

2. Sugg (1966)

Sugg (1966) estimated from survey data the average annual hurricane costs for the United States and Canada as $309.55 million in 1966 dollars. Hurricane damage accounted for $300 million of the total, with the balance split among aircraft reconnaissance, communications, protection of homes and businesses, evacuation, and special interests, including military installations. The cost attributed to special interests was estimated using the following logic:

> A total of six or eight of these [special interests] may be found within a single warning area with losses for any one ranging from $0.025 to $0.1 million and as high as $0.5 million for the Cape Canaveral or the Houston-Galveston areas. Depending upon the area threatened, this figure may vary from $0.4 to $1.8 million for a single storm and would be $0.6 to $2.7 million for the average season. Attempting to weigh these results, one arrives at a crude estimate of $2 million loss for the average hurricane season borne by the special interests.(Sugg, 1966, p. 144)

Using 1966 dollars, Sugg estimated further that the cost of overwarning could range from $7 to $17 million annually and that the hurricane warning service saves about $25 million during an average season and as much as $100 million during a very active season (Sugg, 1966, p. 145).

3. A U.S. Air Force Study (1970)

The United States Air Force directed a study of Air Force response to hurricane forecasts so that the impact of improved forecasts could be estimated. The result was an unpublished memorandum dated December 1970. Eight Air Force bases in the southeastern United States provided information regarding actions taken in response to the setting of hurricane readiness conditions, costs associated with these actions and any history of hurricane activity at that installation. The reports varied greatly. The cost to secure the base ranged from $1,000 to $10,000 in 1970 dollars. The cost of aircraft evacuation ranged from $10,000 to $100,000 in 1970 dollars. On the average, installations evacuated aircraft three or four times for every time they were actually "hit" by a hurricane. Bases were estimated to have been secured against hurricanes twice as often as they were evacuated. The author noted that statistics on how often the actions were actually taken usually were not available. (Air Weather Service, 1970, pp. 1-2)

4. Malone and Leimer (1971)

Malone and Leimer (1971) conducted a study for the U.S. Air Force involving 197 military bases in the western North Atlantic to determine the economic benefit to DOD of improved hurricane forecasts. The following methodology was used to estimate the number of times that hurricane readiness conditions were declared unnecessarily:

a. All tropical storm advisories for the North Atlantic from 1965-1970 were examined in order to identify those installations which received warnings of winds ≥ 50 kt.

b. Two computer programs were written to compensate for the unavailability of complete records at each base. Using the advisories and the mean forecast position errors for 1965-1969, the first program created a theoretical warning area for each forecast and tallied the number of installations falling within the warning area.[16] This step was repeated twice more, first using a 20% reduction in the mean forecast error and then using a 40% reduction in the mean forecast error.

c. The second program identified, using a criterion of winds ≥ 50 kt, which of the installations were actually struck by a particular storm.

d. The results of the two programs were then compared for each storm to determine the number of unnecessary warnings at each level. (Malone and Leimer, 1971, pp. 6-14)

From 1965-1970, the total number of unnecessary warnings for the 197 installations were 170, 408 and 1230 for Conditions I, II, and III, respectively. A reduction of 20% in the mean forecast errors produced a decrease of 18.2%, 23.5%, and 19.8% in the number of times Conditions I, II, and III were set unnecessarily. A 40% reduction resulted in decreases of

[16]Base commanders of installations located within warning areas were assumed to have set the appropriate conditions of readiness.

32.3%, 44.1%, and 42.5% for Conditions I, II, and III when compared to the results using the mean forecast errors. (Malone and Leimer, 1971, p. 15)

Malone and Leimer also estimated preparation costs for a sample of 22 installations in the Atlantic area. Disaster Preparedness Officers at each of the bases provided estimates of direct "out of pocket" preparation costs, costs of manpower diverted from normal duty for storm preparations, and costs of manpower idled by cessation of normal duties (Malone and Leimer, 1971, p. 6). The average preparation costs in 1971 dollars were $124,800 for Condition I, $45,000 for Condition II, and $8,100 for Conditions III and IV combined (Malone and Leimer, 1971, p. 19). Relating these costs to the number of unnecessary warnings, Malone and Leimer concluded that the annual savings to DOD for all western North Atlantic installations would be $1.7 million if there were a 20% improvement in hurricane forecasting and $3.2 million with a 40% improvement (Malone and Leimer, 1971, p. 22).[17]

Neumann (1975) analyzed the data from Malone and Leimer (1971) and concluded that approximately 8.3 military bases lie within an average 300 nm hurricane warning area. The average cost per base in 1971 was found to be $197,000.[18] Adjusting to 1975 dollars, Neumann estimated the

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[17]Malone and Leimer (1971) did not include ship sortie costs or cost savings from decreased damages resulting from better forecasts.

[18]The sum of the average preparation costs per base for Conditions I, II, III and IV is $177,900 ($124,800 + $45,000 + $8,100). Taking the average of each base's total preparation costs yields $177,836.64. $197,000 may be the result of a clerical error.

cost of protection for each installation as $2,458,100. (Neumann, 1975, p. 16)

An unpublished cost study prepared for the National Hurricane Center in 1993 also cited Malone and Leimer (1971) as the most recent comprehensive study on military hurricane preparedness. The average cost of protection per base in 1990 dollars (using $197,000 as the 1971 figure) was estimated as $704,334. Still using 8.3 as the average number of bases per warning area (most likely high due to base closures), the average cost per warning area was approximately $5 billion in 1990 dollars. (National Hurricane Center, unpublished cost study, 1993, p. 64)

5. Anderson and Burnham (1973)

Anderson and Burnham (1973) reported that approximately 15% of hurricane damage to residential and commercial property can be prevented if appropriate measures are taken (White, 1971). Unfortunately, only 20% of the population take protective action (Sugg, 1967) and about $8.64 million in 1971 dollars is lost unnecessarily. (Anderson and Burnham, 1973, p. 126) To estimate a specific region's response to forecast warnings, Anderson and Burnham (1973) used the cost matrix shown in Figure 5, where H is hurricane, H' is no hurricane, A is action taken and A' is no action taken. (Anderson and Burnham, 1973, p. 127) The general form of the Anderson/Burnham model is given in Chapter V.

	H	H'
A	$26,460/1,000 people	$4,000/1,000 people
A'	$44,673/1,000 people	O

Figure 5. Anderson/Burnham Hurricane Protection Model. (after Anderson and Burnham, 1973)

The payoffs, expressed in costs per capita, were derived from Demsetz's study of hurricane damage in Miami, Florida (Demsetz, 1962). Anderson and Burnham hypothesized that the same proportional relationship would hold for all regions. A cost table for a particular locality can be found by multiplying each cell by the area's population, in thousands. The expected value of the two alternatives can be calculated using P_X, the climatological probability of hurricane occurrence in that region.[19] Anderson and Burnham then estimated the potential annual savings as the difference between expected cost with perfect forecasting and the expected cost with no forecasting. Assuming people would not protect in the absence of forecasting, the expected cost of taking no action (the result of (A', H) multiplied by P_X) was used to estimate the expected cost with no forecasting. With perfect forecasting, protection would be taken only when a hurricane

[19]Climatological probabilities can be found in Simpson and Riehl (1981, p. 376).

is inevitable, reducing the expected cost to the result of (A, H) multiplied by P_X. (Anderson and Burnham, 1973, p. 128)

6. Brand and Blelloch (1975)

According to Brand and Blelloch (1975), approximately 100 U.S. Navy and DOD-contracted vessels operate in the western North Pacific at any one time, usually with over half of these ships in port. Ship sortie costs were attributed to fuel consumption, pilot and tug fees, boat transportation to the ship, readying the ship to get underway, and for contracted vessels, the daily rate plus overtime paid to personnel. All cost estimates are given in 1975 dollars.

During threatening conditions, fuel costs per day were estimated as \$1500 for small ships (e.g., destroyers), \$5000 for medium-size ships (e.g., amphibious or supply type) and \$30,000 for large ships (carriers). Pilot and tug fees (for leaving and returning to port) ranged from a few hundred dollars for small ships to over \$5000 for carriers. Costs of boat transportation to ships varied from less than a hundred dollars to thousands of dollars. The costs to "light off" the boilers ranged from hundreds of dollars to thousands of dollars. For those contracted or chartered vessels, the DOD cost of typhoon evasion or delays in ship routing was estimated as \$8000-10,000 per day for each day of lost time. The total annual cost for

typhoon evasion and sortie in the western North Pacific was estimated to reach into the millions of dollars. (Brand and Blelloch, 1975, p. 354.)

Brand and Blelloch (1975) next examined the effects of a 20% improvement in the 48-hour, right-angle forecast error[20] on sortie decisions for Okinawa, given a decision criterion of 30-kt winds. Assuming 200 n mi as the average distance to the 30-kt wind isotach and 145 n mi as the average right-angle forecast error for 48 hours, the authors hypothesized the following scenario: if a storm is approximately 48 hours from Okinawa and the predicted storm track is within 345 n mi (200 n mi + 145 n mi) of Okinawa, then the decision would be to sortie. With a 20% improvement in the 48-h, right-angle forecast error, the critical value drops from 345 n mi to 316 n mi. Each tropical cyclone with a Closest Point of Approach to Okinawa falling in the range from 316 n mi to 345 n mi represents a sortie decision that would have gone the other way had the forecast error been 20% lower. The total number of tropical cyclones per year falling in this range for all eight western North Pacific bases in the sample from 1947-1970 was 5.85. Estimating an average sortie cost of $50,000[21], Brand and Blelloch figured the annual savings attributed to the elimination of 5.85 unnecessary

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[20]The *right-angle forecast error* refers to the perpendicular distance from the forecast position to the best track as determined by post-analysis.

[21]Brand and Blelloch chose $50,000 as the average sortie cost even though they had previously estimated the total cost to be in the millions, because some of the bases in the study are good typhoon havens which eliminates the need to sortie.

sorties per year to be $292,000 in 1975 dollars. (Brand and Blelloch, 1975, pp. 355-357)

C. TROPICAL CYCLONE MISHAP STATISTICS

According to the Naval Safety Center database, from 1 January 1969 to 11 July 1994 there were three incidents reported Navy-wide of ship damage caused by tropical cyclones and incurred while the ship was either moored or anchored. The damage costs given for the three storms were $190,000 in 1989 dollars, $43,800 in 1991 dollars and $12,000 in 1991 dollars, respectively. (Commander, Naval Safety Center Letter, 20 July 1994) In all likelihood, the number of hurricane-related incidents occurring in port is much higher than three; the USS Regulus mishap of 1971 mentioned in Chapter I is conspicuously missing from the report. In fact, the first incident in the report is not until 29 March 1978, nine years into the alleged report period. Estimates of damage costs may be low, as they are based on the damage assessment made by the Commanding Officer reporting the mishap, not on the actual costs to repair. (Brown, 1993, p. 13)

D. HURRICANE EMILY SORTIE COSTS

The Naval Atlantic Meteorology and Oceanography Center (NAVLANTMETOCCEN), Norfolk, Virginia estimated the following sortie costs by ship type for Hurricane Emily in 1993 dollars: CV, $150,000; LHA,

$58,000; CG, $38,000; DD, $35,000; FF, $16,000; SSN, $2,100. The estimated cost for a partial sortie out of Norfolk of 15 ships, eight submarines and 10,807 personnel was $690,000. Forty-five ships remained in port. Charleston, South Carolina did not actually sortie its ships, however, an estimated $212,000 was spent readying 14 ships, five submarines and 4,400 personnel for sortie. (NAVLANTMETOCCEN Norfolk "Hurricane Emily Sortie" brief, 1994)

E. SUMMARY

It is extremely difficult, if not impossible, to make a direct and reliable estimate of the cost-loss ratio as it relates to the hurricane sortie decision. In Chapter V, the CHARM model avoids this problem by letting the confidence level indirectly determine the cost-loss ratio. Although past attempts to quantify the costs of protection and losses due to hurricane damage have produced limited results, it is clear that the cost of unnecessary sorties is not inconsequential. As was discussed in Chapter II, the consequence received depends not only on the decision made, but on the outcomes of numerous random events which are beyond the control of the decision maker. It is this uncertainty which renders invaluable the decision aids reviewed in the next two chapters.

IV. ALTERNATIVE TACTICAL DECISION AIDS

A. INTRODUCTION

This chapter covers some of the existing tactical decision aids (TDA) for assessing hurricane threats. Not all of these decision aids are currently being used by Navy decision makers. Availability and costs are critical issues when considering commercial software packages such as *Enhanced GDS* and *GDS Toolkit* (GDS©, Hazards Management Group, Inc., 1990) and the *Cyclone/Hurricane Acceptable Risk Model* (CHARM©, Science Applications, Inc., 1982). Each decision aid will be discussed in terms of its purpose, features, inputs, advantages and disadvantages (where appropriate) and ability to assist the decision maker with preparation decisions.

B. U.S. NAVY PRODUCTS

1. U.S. Navy Strike and Wind Probability Forecast Program

The U.S. Navy Strike and Wind Probability Forecast Program has been in operational use in the western Pacific since 1979 and in the North Atlantic since 1981. (Turpin and Brand, 1982, p. I-14) Although expressing forecasts in probabilistic terms began as a "parochial U.S. Navy regional effort," the strike probability forecast has been adopted by several government agencies, foreign and domestic, as well as by the private sector. (Jarrell and Brand, 1983, p. 1050) The derivation of strike and wind

probabilities was based on studies of tropical cyclone forecast errors (Jarrell, et al., 1978; Thompson and Elsberry, 1979; Jarrell, 1980; Jarrell, 1981; Neumann and Pelissier, 1981; and Thompson, et al., 1981) and assumes that the forecast errors follow a bivariate normal distribution. Readers interested in a detailed description of the methodology are directed to Jarrell and Brand (1981) and Jarrell and Brand (1983).

Jarrell and Brand (1981) arbitrarily defined a "strike" as occurring when the track of a storm passes within 75 nm to the left or 50 nm to the right of a point of interest (close enough to cause damage). There are two types of strike probabilities, instantaneous and time-integrated. An instantaneous strike probability is the chance in percent that the tropical cyclone will occupy a specific point in space and time (i.e., the probability that the hurricane will hit Norfolk 24 hours from now). A time-integrated strike probability is the probability that the cyclone will strike the point of interest at any time within the forecast period (i.e., the probability that the hurricane will hit Norfolk sometime within the next 24 hours).

Strike probabilities, by themselves, have limited usefulness, because they do not take into account the severity of the storm. Wind probabilities provide a better measure of the threat by incorporating information about the storm's present and forecast wind distribution and maximum wind speed.(Jarrell and Brand, 1983, p. 1052) Since wind probabilities are derived from strike probabilities, the wind probability simultaneously allows

for error in all forecast elements (track, forward speed, maximum wind and wind distribution), making it particularly useful to the decision maker (Jarrell and Brand, 1983, p.1050).

The National Hurricane Center (NHC) forecast provides the input for the U.S. Navy Strike and Wind Probability Forecast Program. While a tropical cyclone is threatening, Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey transmits a strike and wind probability message every six hours. Each message gives both instantaneous and time-integrated strike and 30- and 50-kt wind probabilities at 12-hour increments over a 72-hour forecast period for affected U.S. Navy and coastal Air Force points of interest. Figure 6 shows the message format, HHPIPS, where HH is the forecast period, PI is the instantaneous probability, and PS is the time-integrated probability. Probabilities are rounded to the nearest whole percent. IN means "insignificant," which is defined as less than one percent. (Jarrell and Brand, 1981, p. 183)

```
STRIKE AND WIND PROBABILITY FORECAST
DAVID     030600Z

ROOSEROADS THREAT NIL

GUANTANAMO THREAT NIL

KEY WEST     001MIN 120203 240108 361M06 481M09 601M09 721M10
    50 KNOT  001MIN 122130 240240 361M40 421M40 601M41 721M41
    30 KNOT  000303 124262 240062 360162 481M62 601M62 721M62

PENSACOLA    001MIN 121MIN 241MIN 360101 480105 600107 720108
    50 KNOT  001MIN 121MIN 241MIN 360102 481M04 600105 720107
    30 KNOT  001MIN 121MIN 240101 360206 460109 600210 720112

NEWORLEANS   001MIN 121MIN 241MIN 361MIN 481M01 601M02 721M04
    50 KNOT  001MIN 121MIN 241MIN 361MIN 481MIN 601M02 720103
    30 KNOT  001MIN 121MIN 241MIN 361MIN 481M02 600103 720105

CORPUS CHR THREAT NIL

MAYPORT      001MIN 121MIN 240609 361020 480421 600222 720122
    50 KNOT  001MIN 121MIN 240014 360720 481M20 600121 720121
    30 KNOT  001MIN 120306 242732 361836 480236 600336 720256

CHARLESTON   001MIN 121MIN 241MIN 360407 480413 600214 720215
    50 KNOT  001MIN 121MIN 241MIN 360307 481M10 600211 720213
    30 KNOT  001MIN 121MIN 240102 360915 460317 600410 720319

MOREHD CTY   001MIN 121MIN 241MIN 360101 480205 600208 720211
    50 KNOT  001MIN 121MIN 241MIN 360101 481M03 600206 720209
    30 KNOT  001MIN 121MIN 241MIN 360[illegible] 480107 600310 720313

NORFOLK      001MIN 121MIN 241MIN 361MIN 460102 600206 720209
    50 KNOT  001MIN 121MIN 241MIN 361MIN 481M01 600206 720308
    30 KNOT  001MIN 121MIN 241MIN 361MIN 460103 600307 720311

NEW LONDON   001MIN 121MIN 241MIN 361MIN 481MIN 601M01 720103
    50 KNOT  001MIN 121MIN 241MIN 361MIN 481MIN 601M01 720104
    30 KNOT  001MIN 121MIN 241MIN 361MIN 461MIN 600101 720205

BERMUDA      THREAT NIL

FOR METEOROLOGISTS: FORECAST CONFIDENCE TABLE
     TIME PROB DIST PROB DIST PROB
     12HR  54   50   27   75   14
     24HR  53  100   25  150   22
     48HR  36  200   26  300   38
     72HR  29  300   24  450   47

PROBABILITIES BASED ON FOLLOWING FORECAST
[illegible]
```

Figure 6. Strike and Wind Probability Message.
(from Jarrell and Brand, 1981)

Because the time-integrated event includes many instantaneous events, time-integrated probabilities will be at least as large as the instantaneous probabilities and usually much larger. Instantaneous probabilities are more useful to decision makers concerned with moving targets (i.e., ships), whereas users at fixed locations (i.e., cities, bases) will prefer the time-integrated probabilities. (Jarrell and Brand, 1983, pp. 1050-1052)

In general, it is better to compare probabilities at several sites rather than to try to interpret the magnitude of the probability at a single point of interest. This practice may help the decision maker who might be inclined to ignore a 72-hour strike probability of "only" 10%.[22]

The Navy Wind and Strike Probability Users Manual (Turpin and Brand, 1981) suggests using as a starting point the following threshold values of time-integrated strike probabilities for the setting of hurricane threat conditions:

Set Condition:	If the Time-Integrated Strike Probability is:
IV	≥ 5% within 72 hours
III	≥ 10% within 48 hours
II	≥ 20% within 24 hours
I	≥ 30% within 12 hours

Decision makers are cautioned against ordering a higher condition of readiness based on these objective criteria without giving further

[22]The National Weather Service (NWS) issues their own hurricane and tropical storm probabilities for 44 selected locations from Brownsville, Texas to Eastport, Maine. The NWS defines the probability of a strike as the likelihood that the center of the storm will pass within 65 miles of the point of interest(i.e., within the radius of hurricane force winds for an average storm) at the forecast time. This is analogous to the instantaneous strike probability issued by the U.S. Navy. Using this definition, if a storm is forecast to be directly over the point of interest in 72 hours, the maximum probability is 10%! At 48 hours from predicted landfall, the maximum probability is 13-18%. At 36 hours, the maximum probability is 20-25%. At 24 hours, the maximum probability is 35-45%. When the storm is less than 24 hours from forecast landfall the values increase more rapidly, reaching up to 60-70%. (Lee County Division of Public Safety, 1993)

consideration to the individual circumstances of the threat. (Turpin and Brand, 1982, p. I-17)

The CHARM model in Chapter V provides another objective measure of the threat; however, that model relies on 30- and 50-kt wind probabilities rather than on strike probabilities. Chapter VI addresses the accuracy of these probability forecasts.

2. ATCF and ATCFjr

The Automated Tropical Cyclone Forecasting (ATCF) System, Version 2.6 (Miller, et al., 1988) is a microcomputer-based forecasting tool that was designed to replace the grease pencils, acetates, clipboards and paper records that were still in use at the Joint Typhoon Warning Center, Guam in 1989. The following are some of the forecasting functions performed by ATCF: plot fixes of storm location, plot forecast tracks, evaluate the plotted information (including various objective forecast tracks) and make position and wind forecasts, compute forecast errors and other statistics, prepare messages and make best tracks. (Miller, et al., 1989, p.1)

ATCFjr, Version 2.73 (Miller, et al., 1993) is the short version of ATCF. ATCFjr is a menu-driven IBM compatible software package that allows the user to graphically display and analyze an official tropical cyclone warning. The data from the NHC warning message can be entered manually or retrieved automatically using ATCFjr's decoder. ATCFjr can then be used

to display against various map backgrounds the cyclone track, the size of the hurricane and the position of wind radii. ATCFjr will also compute the closest point of approach (CPA) to any location (longitude/latitude) in the system. (Miller, et al., 1993, p.1)

CDR Lilly, Operations Officer, NAVLANTMETOCCEN Norfolk expressed some concerns about ATCFjr's user-friendliness, finding the program to be geared more toward the forecaster than the decision maker. Furthermore, ATCFjr does not incorporate strike and wind probabilities. (Telephone conversation between CDR Lilly, NAVLANTMETOCCEN Norfolk and the author, 9 May 1994) FNMOC has already identified as an action item the correction of the latter deficiency. (Interview between Mary Clifford, FNMOC, Monterey and the author, 13 May 1994).

C. HURRICANE HAVENS HANDBOOK FOR THE NORTH ATLANTIC OCEAN

Developed by the Naval Environmental Prediction Research Facility (now the Naval Research Laboratory, Monterey), The Hurricane Havens Handbook for the North Atlantic Ocean (Turpin and Brand, 1982) evaluates 22 deep water ports as to their suitability as hurricane havens for the Atlantic fleet. The purpose of the Handbook is to aid commanders and commanding officers in the assessment of hurricane threats. (CINCLANTFLT Letter, 13 April 1982)

For each port, detailed descriptions are given of the port location, surrounding topography, harbor and harbor facilities, including heavy weather facilities and hurricane anchorages. In addition, the following areas of concern are addressed:

1. tropical cyclone climatology for the port;
2. effects of topography on hurricane-associated winds and seas;
3. effects of storm surge, tide and wave action within the harbor;
4. factors to consider when deciding whether to evade at sea or remain in port. (Brand, 1978, pp. 375-377)

The first section of the Handbook provides general guidance on warnings, forecasts and hurricane sortie decisions. Figure 7 contains a graph from this section which displays a few of the factors that affect the "leave/stay" decision. (Turpin and Brand, 1982, p. I-2) It is easy to see how a decision maker could be somewhat daunted by the number of variables that need to be considered.

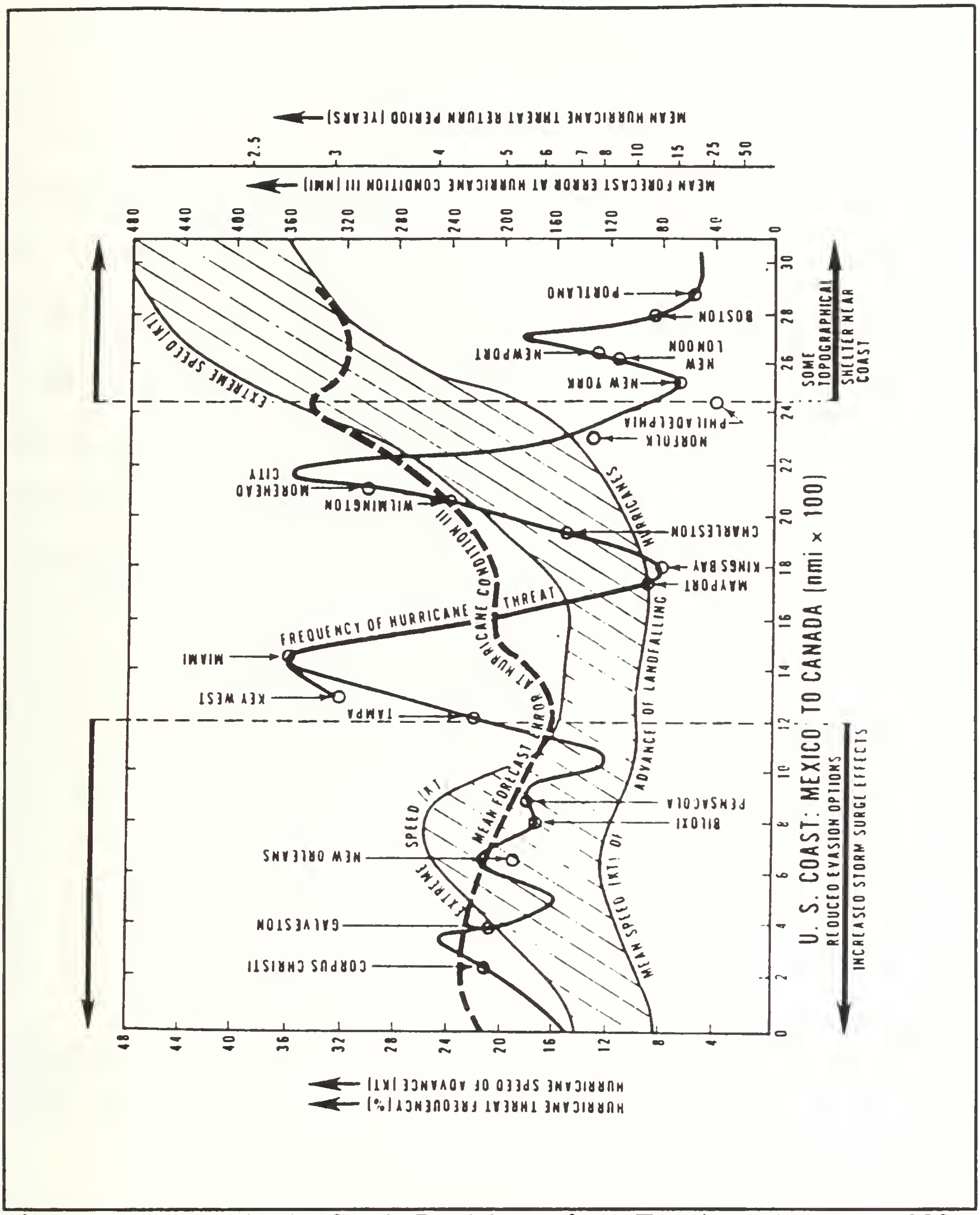

Figure 7. Factors in the Sortie Decision. (from Turpin and Brand, 1982)

Also contained in this section is an interpretation of the Near Pass Probability charts included with each port evaluation. These charts can be used to find the probability that a tropical cyclone will pass within 180 n mi of a point of interest. Turpin and Brand (1982) recommended that the actual and forecast positions of a tropical cyclone be plotted on the chart appropriate to the time of year. At three days and beyond, the climatological probabilities can provide prior notice of a possible encounter up to six days in advance. As soon as the position of the tropical cyclone reaches the 3-4 day time line, attention should be turned to the strike and wind probability forecasts. (Turpin and Brand, 1982, p. I-5) An example of a Near Pass Probability chart is given in Figure 8 (Turpin and Brand, 1982, p. II-10).

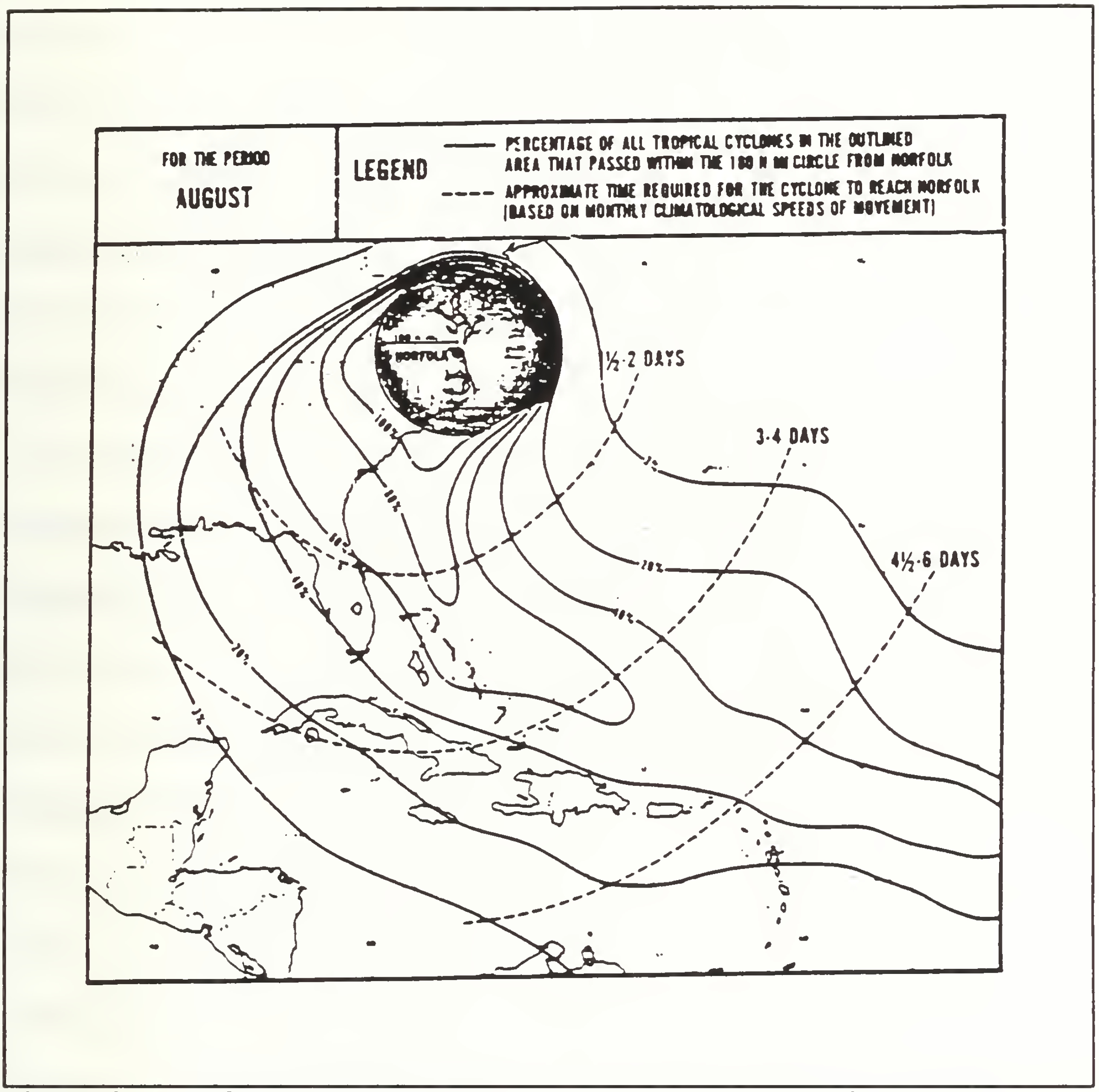

Figure 8. Norfolk, Virginia Near Pass Probability Chart for August. (from Turpin and Brand, 1982)

The selection of a 180 n mi radius around the point of interest was a concession made to the Handbook users. Jerry Jarrell, National Hurricane Center, insists that a typical size hurricane would probably not have any effect this far away from the point of landfall, much less cause damage. For the maximum extent of severe damage, the National Hurricane Center uses 75 n mi to the left of center and 50 n mi to the right, coincident with the definition of strike used in the derivation of the U.S. Navy Strike and Wind Probabilities. According to Jarrell, when a smaller, more reasonable radius was used, Navy decision makers were disappointed that the resultant probabilities were so low.[23] Increasing the radius to 180 n mi artificially inflated the strike probabilities to 20-30%. (Interview between Jerry Jarrell, National Hurricane Center, Miami and the author, 6 June 1994).

<u>The Hurricane Havens Handbook for the North Atlantic Ocean</u> is a tremendously valuable source of information. Decision makers who may someday face a hurricane sortie decision should, at a minimum, be familiar with the section pertaining to their port and with the general guidance provided in Section I. However, for <u>specific</u> actions to be taken when severe weather threatens, the Handbook defers to the local destructive weather instructions.

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[23]This is not surprising. Individuals tend to discard low probability events and ignore high probability events, focusing their attention on the middle range of probabilities that lie within their cognitive threshold (Douglas, 1985, p. 30).

D. LOCAL DESTRUCTIVE WEATHER INSTRUCTIONS

The Destructive Weather Plan for Norfolk, Virginia was reviewed as an example of a local destructive weather instruction. The stated purpose of the plan is: ". . . to publish guidance and procedures to be employed by commands and activities in the SOPA Hampton Roads area in the event of destructive weather (tropical storms, hurricanes, thunderstorms, tornadoes, gales, and severe windstorms)." (COMNAVBASENORVA/SOPA (ADMIN) HAMPTONINST 3141.1S, 18 May 1993, p.1)

In the Destructive Weather Plan, definitions of the different storm systems, warnings and readiness conditions are given as well as the actions required to achieve each condition of readiness. The section entitled "Sortie and Evasion" states clearly and succinctly the main points from the Hurricane Havens Handbook for the North Atlantic Ocean, stating in no uncertain terms the options and risks, while adding essential information about the timing of the sortie decision:

> The Fleet should be prepared to get underway at, or shortly after, Condition III (destructive winds expected within 48 hours). The following time considerations are critical factors of a sortie decision:
>
> (1) Night sorties should be avoided due to safety of navigation (possible delay of 8 hours, or longer).
>
> (2) A Norfolk sortie will require nearly 12 hours to get all ships underway.

(3) Sea and Anchor details will be approximately 3 hours long due to limited harbor pilot assets and shipping congestion.

(4) Due to potential storm recurvature and inherent forecast error, ships will usually need to run nearly 200 nm to comfortably evade the storm (13 hour transit at 15 kts). This transit will be in less than optimal sea states due to rapid swell propagation in advance of tropical cyclones.

Factoring in the above delays, total time of storm evasion from pierside, for ships in the latter stage of a major sortie, could take more than 36 hours. (COMNAVBASENORVA/SOPA(ADMIN)HAMPTONINST 3141.1S, 18 May 1993, p.4)

E. ENHANCED GDS AND GDS TOOLKIT

Enhanced GDS and GDS Toolkit (GDS©, Hazards Management Group, Inc., 1990) together provide a powerful hurricane response tactical decision aid. Using the forecasts and storm information contained in the Public and Marine Advisories[24] issued by the National Hurricane Center, Enhanced GDS performs all of the functions of a basic hurricane tracking program such as ATCFjr. GDS Toolkit contains utility programs and files for use with Enhanced GDS. A few of the features in Enhanced GDS not included in ATCFjr will be described here, as well as two of GDS Toolkit's subprograms.

The NAVLANTMETOCCEN Norfolk purchased Enhanced GDS for $600 following a Hazards Management Group demonstration at a hurricane

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[24]Marine advisories are normally issued four hours after the forecasts are made, therefore the forecast positions are valid for times 8, 20, 32, 44 and 68 hours following the time the Marine Advosory is issued. (Hazards Management Group, Inc., 1990, p. 4)

conference. In terms of the system's adaptability to military use, only one drawback was noted: all of the times are given in local time, not Zulu. (Telephone conversation between CDR Lilly, NAVLANTMETOCCEN Norfolk and the author, 9 May 1994) GDS Toolkit, which includes GDS Chart, GDS Grab, GDS Bootstrap and Shiftrack, costs $195 and must be used in conjunction with Enhanced GDS. (Hazards Management Group, Inc., 1990, p. 25)

1. Enhanced GDS

The amount of time remaining for storm preparations can be found based on three different scenarios. <u>Assuming forecasts are correct</u>, Enhanced GDS will calculate how much time remains before either the storm center or winds of a certain velocity reach the closest point of approach (CPA) to a point of interest. If the storm is not currently forecast to pass near the point of interest or to reach its CPA soon, the decision maker may want to see a "worst case" calculation made using the assumption that the storm will take a <u>direct path</u> to the point of interest. For this calculation, Enhanced GDS can use either the storm's current forward speed or the forecast forward speed. The third alternative incorporates into the calculation the <u>average error</u> made by the National Hurricane Center. This often provides the most plausible estimate of the time remaining. (Hazards Management Group, Inc., 1990, p. 7)

Decision makers may want to know how much time they have left before they must decide whether or not to initiate a particular response action. Enhanced GDS has two features that can assist the decision maker in keeping track of these decision points. First, the decision maker provides optimistic, normal and pessimistic estimates of "lead times" needed to complete the various response actions. Then, using any of the assumptions discussed above as the criterion for the interruption of storm preparations, Enhanced GDS will compute for different storm intensities the time remaining until the initiation of each response action is required. The results are presented in tabular form. (Hazards Management Group, Inc., 1990, p. 8)

The second option graphically represents the response lead time requirement and the storm intensity (size and forward speed) as a "Decision Arc" or "Encroachment Circle" around the point of interest. When the storm's "wind field" or isotach for a particular wind speed reaches the decision arc, the response must be initiated if it is to be finished before the winds arrive at the point of interest. Enhanced GDS will calculate the time remaining before the circles intersect. (Hazards Management Group, Inc., 1990, p. 8)

At this point, the decision maker knows <u>when</u> to decide, but not <u>what</u> to decide. To help decision makers resolve their protect/do not protect dilemmas, Enhanced GDS incorporates into a number of its maps and tables

the probability forecasts from the National Weather Service's Public Advisory. When interpreting these numbers, it is important to realize that the probabilities reported are total cumulative probabilities for the forecast period, analogous to the time-integrated strike probabilities issued by the U.S. Navy. There is an opportunity for confusion here. Because probabilities are a measure of forecast error and forecast error increases with time, it should be expected that the probabilities would be much lower when the hurricane is three days from landfall than when the hurricane is only one day from landfall. This is indeed the case; however, since the probabilities given are cumulative in nature, it may not be readily apparent. The Users Guide suggests using the probability forecast in the following way:

> ...when you have reached a decision point (say, 32 hours before center's CPA),...compare the probability *for the corresponding time frame* to a probability threshold you've *determined in advance*. If the current probability is greater than the threshold value, initiate the response, if not, don't. **Which probability value to use as a threshold is not a technical matter, it is a matter of your willingness to take risk.** Some people use 30%, some use lower probabilities for stronger storms, and some use the ratio of their probability to the highest to ever be expected for a particular time frame. (Hazards Management Group, Inc., 1990, p. 10)

As another aid to decision makers, Enhanced GDS graphically depicts the uncertainty in the position forecasts using "probability ellipses." For example, a 50% ellipse drawn around the 24-hour forecast means that there

is a 50-50 chance the actual 24-hour position will be somewhere within the ellipse. The value of this approach is that it keeps the decision maker from focusing on a point (which is probably wrong) and instead has the decision maker consider an area where the center of the storm might be. Increasing the confidence level necessarily increases the size of the ellipse. (Hazards Management Group, Inc., 1990, p. 11) Another display using ellipses that a decision maker might find useful shows two concentric ellipses around a forecast position, where the inside ellipse is the probability ellipse and the outer ellipse is an isotach for a particular wind speed. The isotach is drawn by assuming the center of the storm is located somewhere on the periphery of the probability ellipse. Enhanced GDS will also plot around a forecast position a "probability grid" which is a 99% probability ellipse divided into many segments, each with a .5% chance of containing the center of the storm. (Hazards Management Group, Inc., 1990, p. 12) This spiderweb-like grid provides the basis for determining strike probabilities, although the actual calculations and methods are far more complex.

The uncertainty in the intensity (maximum sustained wind speed) of the hurricane is displayed by Enhanced GDS using a histogram. Starting with the current wind speed, Enhanced GDS gives the probability (up to 90%) that the winds will not exceed certain speeds. (Hazards Management Group, Inc., 1990, p. 13)

2. GDS Bootstrap

According to the Users Guide, the hardest part of decision making is: ". . . developing a decision system in which the various types of threat information are integrated and weighed against one another to produce an overall evaluation indicating an appropriate response." (Hazards Management Group, Inc., 1990, p. 16) GDS Bootstrap enables the decision maker to derive a utility function that reflects the decision maker's own values and preferences regarding hurricane threats. Figure 9 contains a table of hypothetical hurricane threat information. (Hazards Management Group, Inc., 1990, p. 16)

HYPOTHETICAL HURRICANE THREATS

NHC Alert	MPH	CPA Time (hrs)	CPA Distance (mi.)	34 KT Winds (mi.)	Forward Speed (mph)	Probability (%)	RESPONSE (0 - 100)
NONE	65	48	300	100	5	5	
WATCH	65	24	10	150	25	5	
WATCH	115	24	10	100	15	50	
WARNING	165	12	100	100	25	20	
NONE	115	48	300	200	25	50	
WATCH	165	24	10	200	5	20	
NONE	165	24	100	100	15	5	
WARNING	65	48	10	150	15	50	
NONE	165	12	10	200	15	50	
WATCH	65	48	100	200	25	20	
WARNING	165	24	300	150	25	50	
WATCH	165	48	100	100	5	50	
WARNING	115	12	100	150	5	50	
WARNING	165	48	10	200	25	5	
NONE	65	12	10	150	5	20	
WATCH	165	12	300	150	5	5	
NONE	165	48	300	150	15	20	
WARNING	115	48	10	100	5	20	
WARNING	115	24	300	200	5	5	
NONE	115	24	100	150	25	20	
WATCH	115	48	100	150	15	5	
NONE	65	24	100	200	5	50	
WATCH	115	12	300	200	15	20	
NONE	115	12	10	100	25	5	
WARNING	65	24	300	100	15	20	
WARNING	65	12	100	200	15	5	
WATCH	65	12	300	100	25	50	

Figure 9. Hypothetical Hurricane Threat Information for GDS Bootstrap. (from Hazards Management Group, Inc., 1990)

The following are instructions to the decision maker for using GDS Bootstrap:

> In many instances we are unable to articulate precisely how we make decisions, even if we follow a very consistent procedure for making them. To get around that obstacle we ask you to tell us how you believe you would respond to each of several specially constructed hypothetical hurricane threats. Although some of the threats are highly unlikely (if possible at all) they have the statistical property of allowing us to separate out the weight you place on each of the seven bits of information and to "capture" the process you used to evaluate the threats.(Hazards Management Group, Inc., 1990, p. 16)

GDS Bootstrap incorporates the decision maker's responses into a customized program. Then, during a real hurricane threat, the decision maker can run Bootstrap and obtain a response value based on the logic used in responding to the hypothetical threats. The response value can be related to recommended response actions appropriate to that level of threat. (Hazards Management Group, Inc., 1990, p. 17)

Without any data, it is difficult to assess whether GDS Bootstrap is worth the amount of time it would take to evaluate 27 hypothetical threats, each with seven pieces of information. GDS Bootstrap may be asking too much of our decision maker.[25] This would be a difficult proposition even for an experienced forecaster (on the other hand, it may actually be harder for the forecaster to respond to what he knows are impossible scenarios).

[25]When presented with eight important attributes of risky investments, business managers focused on only one or two attributes. Cognitive psychologists and artificial intelligence experts ascribe this to people's limited capability for processing information. (MacCrimmon and Wehrung, 1986, pp. 138-141)

Furthermore, the decision maker is given no feedback that the decision process he is using is consistent, as is assumed. Traditionally, utility curves are derived through a carefully structured personal interview where the decision maker is shown his inconsistencies and is allowed to change his answers to achieve consistency if so desired. Even if the decision maker is responding consistently to the threats, how will he know he is not consistently wrong? Finally, it is irrelevant if the decision maker is optimizing his individual utility curve. What is needed is a utility curve for the organization, in this case, the U.S. Navy. Efficiency will be achieved when all of the Navy decision makers adopt the same hurricane response policy, not when each decision maker acts in accordance with his own attitudes toward risk.

3. Shiftrack

Shiftrack starts with actual hurricane threats and adapts them to any selected location. GDS Toolkit provides the decision maker with storm data files and forecasts for 25 historical Gulf of Mexico and Atlantic hurricanes (in addition to the files for Allen, Elena, Gloria, and Hugo which come with Enhanced GDS). The decision maker simply selects a storm from the archives and specifies where he wants it to hit. Shiftrack automatically modifies the storm coordinates and forecasts. The result is a new storm file that can be run with GDS. Working through the storm's development, the

decision maker can hone his skills by deciding how he would respond to each advisory. (Hazards Management Group, Inc., 1990, p. 18)

F. CHARM

The *Cyclone/Hurricane Acceptable Risk Model* (CHARM ©, Science Applications, Inc., 1982) is a dynamic, computer-based hurricane risk assessment model that uses a historical hurricane track data base, a forecast error data base, a forecast simulation program and the real-time NHC current forecast to provide the equivalent experience of "thousands of forecasters". CHARM translates this experience into strike and wind probabilities and a product called Earliest Time to Expect (ETE). ETE is based on a user-selected confidence level and answers the question, "Based on historical hurricane movement through this geographical area, what is the minimum time I have until the hurricane hits us?" CHARM can also be used to predict storm surge and flooding. (Telephone conversation between Charles Neumann, Science Applications International Corporation and the author, 7 June 1994)

The next chapter discusses another Science Applications product, the CHARM model for setting hurricane readiness conditions, which uses much of the technology that went into the risk assessment model of the same name.

V. THE CHARM MODEL

A. INTRODUCTION

Sortie decisions in the face of an approaching hurricane are largely based on the storm forecast track (Brand and Blelloch, 1975, p. 355) and the likely maximum wind that will be experienced at the location of interest.[26] (Kostyshack and Jarrell, 1984, p. 2) Appleman (1962) suggested using wind probability forecasts as a decision criterion: "It may be that the various commanders on the base will either have or wish to formulate plans that are put into operation when the probability of the base being struck by above-critical wind speeds exceeds a certain value." (Appleman, 1962, p. 22) Jarrell and Brand (1983) expanded on the role that wind speed plays in the decision process, theorizing that there exists a destructive wind level (e.g., 50 kt) for which preparations must be made, and a lower wind level (e.g., 30 kt) which prohibits most preparations. This became known as the Cyclone/Hurricane Acceptable Risk Model (CHARM) concept.(Kostyshack and Jarrell, 1984, p. 2) Unfortunately, standard forecasts only predict wind speeds of the cyclone and leave it up to the individual decision makers to interpret how the storm will affect them. Wind probability forecasts pick up

[26]Actually, the sortie problem is related more to the hurricane's outer wind structure or size (e.g., 30- and 50-kt wind radii) than to the storm track or intensity.

where the standard forecasts leave off by quantifying the threat at specific sites.

The CHARM model uses these wind probabilities to set conditions of readiness at a user-specified confidence level. The development of the CHARM model was accomplished through a procedure called SETCON (Kostyshack and Jarrell, 1984, pp. 5-12) which is outlined in the next section. The results of the model will be interpreted, followed by a discussion of the findings and recommendations for refinements and applications.

B. METHODOLOGY

Kostyshack and Jarrell (1984) were interested in developing a model based on the CHARM concept that would help to minimize the risks associated with decision-making based on imprecise forecasts. (Kostyshack and Jarrell, 1984, p. 1) The procedure was SETCON; the product was a tactical decision aid for setting hurricane conditions of readiness. In the original study, CHARM nomographs were introduced for Key West, Florida and Guantanamo Bay, Cuba. Key West will be used here to illustrate the model methodology and features because of a wind probability bias in the Guantanamo Bay results.

Using CLIPER[27] (Neumann, 1972) and current forecast error characteristics, procedure SETCON created a large data set of simulated forecasts (approximately 10,000) for 197 actual hurricanes that passed within 360 n mi of Key West from 1899-1979. For each hurricane, multiple independent forecast tracks were generated from the same starting point, located on the archived storm track 72 hours prior to the storm's closest point of approach to Key West. Storm position, maximum wind speed and time-integrated 30- and 50-kt wind probabilities (P_{30} and P_{50}) for Key West were forecast for 12, 24, 48 and 72 hours from the initial position.

The actual hurricanes were then "hindcasted" or backcasted to determine when conditions of readiness should have been set at Key West, based on the time when hurricane force winds were observed there. Because the maximum wind experienced at a specific location was not directly available from the tropical cyclone track archive, it was estimated from the latitude, storm motion and center wind speed. The following notation was used to set the tropical cyclone hindcast conditions for Key West:

H1: winds ($\geq$ 64 kt) occurred at Key West within 12 hours;

H2: winds ($\geq$ 64 kt) occurred at Key West within 24 hours;

---

[27]CLIPER is a regression equation forecasting model which uses predictors derived from climatology and persistence.

H3: winds ($\geq$ 64 kt) occurred at Key West within 48 hours;

H4: winds ($\geq$ 64 kt) occurred at Key West within 72 hours.

Next, the simulated forecasts were compared to these hindsight estimates of actual conditions.(Kostyshack and Jarrell, 1984, pp. 13-15) Figure 10 shows the results of these comparisons. Each point plotted on the CHARM nomograph for Condition II represents the ordered pair of wind probabilities, (P_{30}, P_{50}), taken from a forecast of a cyclone that in hindsight is known to have caused hurricane-force winds at Key West between 12 and 24 hours later (in short, H2 was set). Plots for H1, H3 and H4 were constructed in a similar manner.

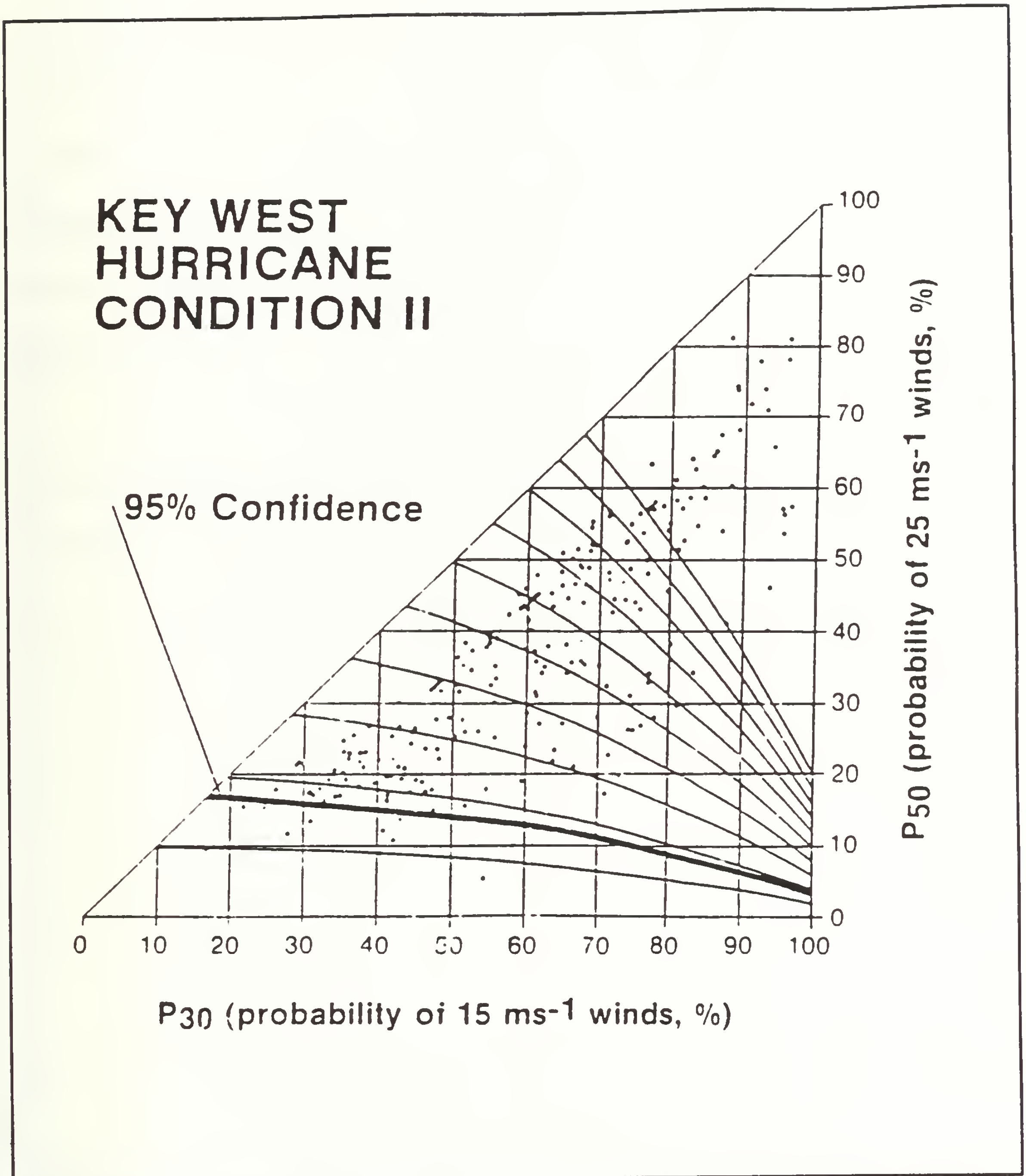

Figure 10. CHARM Nomograph Showing the Scatter Plot of (P_{30}, P_{50}) Values. (from Kostyshack and Jarrell, 1984)

The heavy curved line in Figure 10 is the warning condition threshold that resulted from the user choosing a 95% confidence level. The user's selection of this confidence level means that the user desired that Condition II be set in at least 95% of the occasions that warranted it. Ninety-five percent of the points lie above and to the right of the threshold and indicate the occasions in which Condition II would be correctly set; the remaining 5% lying below the curve represent the times when Condition II would not be set even though hindcast conditions called for it. The derivation of the family of curves will be covered in the next section.

Thresholds were determined for each condition of readiness and then combined on a single nomograph, minus the probability plots. Figure 11 shows a completed nomograph for Key West.

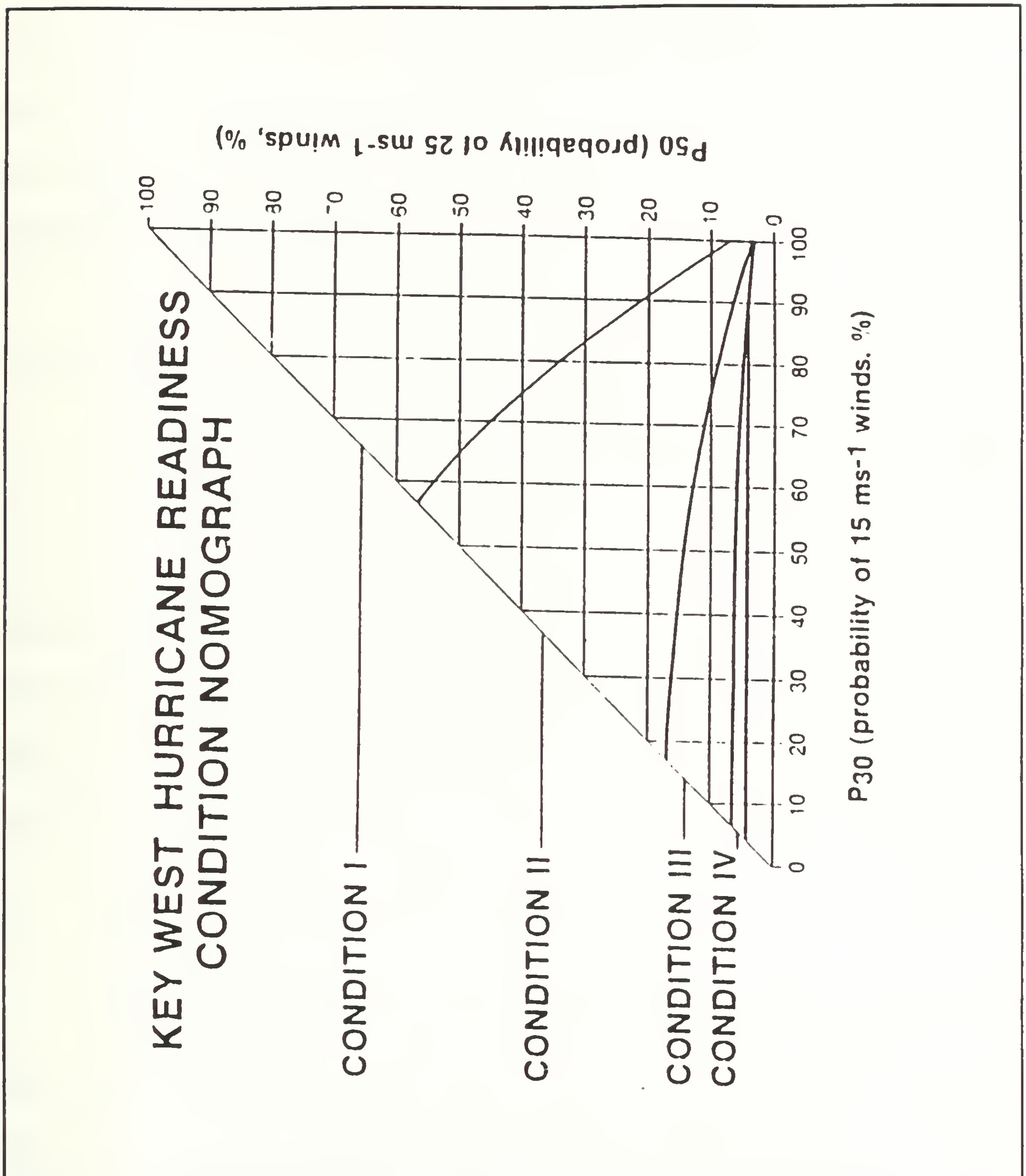

Figure 11. Key West Hurricane Readiness Condition Nomograph. (from Kostyshack and Jarrell, 1984)

The authors recommended photocopying the nomograph and using a separate graph to track each hurricane. Wind probability forecasts are issued every six hours. The graph should be entered with the (P_{30}, P_{50}) values from the maximum forecast available (usually the 72-hour forecast) and should be updated with each new forecast. The zones between the thresholds represent recommendations as to which condition of readiness should be set, if any. (Kostyshack and Jarrell, 1984, p. 19)

Figure 12 shows the consecutive forecast wind probabilities from Table 1 plotted on a CHARM nomograph.

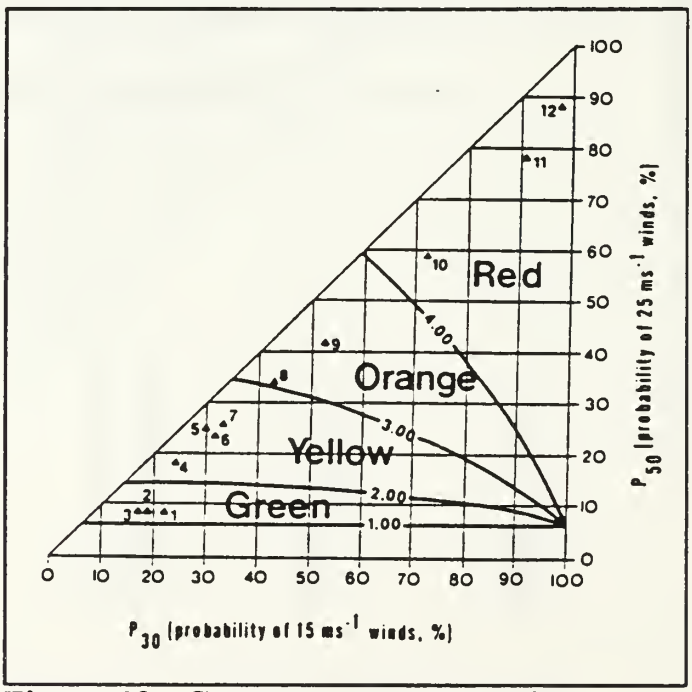

Figure 12. CHARM Nomograph for Setting Color-Coded Conditions. (from Jarrell and Brand, 1983)

Actual time to strike	Forecast maximum wind (ms^{-1})	Forecast CPA (km)	Forecast P_{50} (%)	P_{30} (%)	Forecast CHARM threat
72 h	15	140	12	22	1.62 green
66 h	25	85	12	19	1.61 green
60 h	50	0	12	17	1.61 green
54 h	50	0	18	24	2.15 yellow
48 h	20	220	23	32	2.42 yellow
42 h	10	250	24	30	2.46 yellow
36 h	10	240	26	34	2.58 yellow
30 h	15	165	33	43	3.01 orange
24 h	25	185	42	52	3.35 orange
18 h	60	93	59	73	4.27 red
12 h	60	75	78	91	4.72 red
6 h	60	35	88	98	4.87 red

Table 1. Comparison of Threat Indices to the City of Rosseau as Hurricane David Approached in August 1979. (from Jarrell and Brand, 1983)

In this example, the thresholds represent arbitrary cost-benefit ratios. Conditions I, II, III and IV are color-coded as Red, Orange, Yellow and Green, respectively. The plots correctly show a steady trend of increasing threat over the three-day period. (Jarrell and Brand, 1983, p. 1056)

C. DERIVATION OF THE CHARM CURVES

The family of curves in the CHARM nomographs were derived from the cost-loss ratio described in Chapter II. Kostyshack and Jarrell (1984) refer to it as a Cost-Benefit Ratio (CBR). They maintain that, while the CBR is a useful decision criterion, it is impossible to determine in advance of a hurricane and is impossible to estimate directly. SETCON resolves this

problem by indirectly estimating the CBRs. (Kostyshack and Jarrell, 1984, pp. 2-4) The user selects the confidence level, the confidence level specifies the threshold curve, and each curve can be related back to the equation from which it was derived. The following assumptions were made:

1. Thirty-knot winds interrupt preparations, therefore these preparations must be started sufficiently in advance of 30-kt winds to allow for their completion.

2. Losses occur with the arrival of 50-kt winds.

3. The fraction of preparations completed is $(1 - P_{30})$.

4. The fraction of preparations completed will prevent the same fraction, $(1 - P_{30})$, of avoidable damage.

5. The decision maker is risk neutral.

The cost matrix associated with this model of the cost-loss ratio situation is depicted in Figure 13 where the actions are denoted by P (start to prepare) and P' (do not start to prepare), the states are denoted by W ($\geq$ 50 kt winds occur) and W' ($<$ 50 kt winds occur), C is the cost of preparation and L is the loss due to avoidable hurricane damage.

	W	W'
P	$(1-P_{30})C$ $-(1-P_{30})L$	$(1-P_{30})C$
P'	L	O

Figure 13. CHARM Cost Table. (after Kostyshack and Jarrell, 1984)

If the decision criterion is to minimize expected losses, the optimal decision is to protect (set the appropriate condition, start to prepare) if:

$$P_{50}(1 - P_{30})(C - L) + (1 - P_{50})(1 - P_{30})C < P_{50}L \qquad 5.1$$

This simplifies to:

$$(1 - P_{30})C < (2 - P_{30})P_{50}L \qquad 5.2$$

or

$$[(2 - P_{30})/(1 - P_{30})P_{50}] > C/L \qquad 5.3$$

Curves in the CHARM nomographs were obtained by setting the cost-loss ratio (C/L) equal to values from zero to one, assigning P_{30} to values from zero to one and solving for P_{50}, assuming equality for the above relationship.

Note that it is impossible for P_{50} to exceed P_{30}.(facsimile from Jerry Jarrell, NHC to the author, 9 June 1994)

D. ANALYSIS

A confidence level of .95 for all four hurricane readiness conditions was selected for the Key West study. This resulted in CBR values of .78, .17, .062 and .04 for Conditions I, II, III and IV, respectively. (Kostyshack and Jarrell, 1984, p. 15) Figure 14 displays the results using simple two-way contingency tables, where W denotes that hurricane force winds (≥ 64 kt) occurred, W' denotes that hurricane force winds did not occur, P denotes that the relevant hindsight condition H_i (i = 1, 2, 3, 4) was set, and P' denotes that H_i was not set. (Kostyshack and Jarrell, 1984, p. 17) All values represent frequencies or percentages.

Condition I

	W	W '	Total
P	58.1	41.9	100.0
P '	0	0	0.0
Total	58.1	41.9	100.0

Condition II

	W	W '	Total
P	25.1	40.9	66.0
P '	0.9	33.1	34.0
Total	26.0	74.0	100.0

Condition III

	W	W '	Total
P	10.6	62.1	72.7
P '	0.2	27.1	27.3
Total	10.8	89.2	100.0

Condition IV

	W	W '	Total
P	2.4	32.3	34.7
P '	1.5	63.8	65.3
Total	3.9	96.1	100.0

Figure 14. Results Using CHARM Nomograph for Key West to Set Hindsight Conditions. (after Kostyshack and Jarrell, 1984)

The contingency table for Condition III will be used to illustrate how easily the results can be interpreted in this format. The probability of committing a type I error in setting Condition III (protecting when adverse weather does not occur) is .621. In this thesis, the probability of this kind of error is equivalent to the *overwarning rate*. The probability of a type II error (failing to protect when it is warranted) is .002. The percentage of correct calls (37.7%) is obtained by adding the outcomes associated with combinations (P, W) and (P', W'). Of those cases where hurricane-force winds subsequently occurred, 98% (10.6 of 10.8) were preceded with wind probabilities exceeding the lower threshold for setting Condition III. This percentage can also be expressed as Pr(P | W), or the probability of protecting, given that we know that adverse weather occurred. These results for Conditions III, as well as those for I, II, and IV are summarized in Table 2.

	CONDITIONS			
	I	II	III	IV
Type I: Pr (P, W ')	41.9%	40.9%	62.1%	32.3%
Type II: Pr (P ', W)	0.0%	0.9%	0.2%	1.5%
Correct call:				
Pr (P, W) + Pr (P ', W ')	58.1%	58.2%	37.7%	66.2%
Correct warning: Pr (P | W)	100.0%	97.0%	98.0%	62.0%

Table 2. Summary of Results Using CHARM Nomograph for Key West to Set Hindsight Conditions. (after Kostyshack and Jarrell, 1984)

In the original study, Kostyshack and Jarrell (1984) analyzed the data in terms of the timing of the action taken. The condition could be set "early," "on time," or "late." These categories were translated into the P and P' used in Figure 14 by interpreting those cases labeled "early" and "on time" as occasions where the condition was set, and "late" as meaning the condition was not set (though eventually some condition was set in every case). Also, since the tropical cyclones were only analyzed up to 72 hours before passing Key West, it was not possible to set Condition IV early. (Kostyshack and Jarrell, 1984, p. 16)

The data were also examined from the viewpoint that the action taken could be "too strong" (overwarning), "correct", or "too weak" (underwarning). The term "overwarning" may lead to some confusion. The authors inadvertently used overwarning to describe all cases where adverse weather

did not occur. In this thesis, overwarning refers to all cases where the condition was set unnecessarily (a type I error). This difference in meaning led Kostyshack and Jarrell to report overwarning rates of 41.9%, 74.0%, 89.2%, and 96.1% for Conditions I, II, III, and IV, respectively, whereas this author finds the overwarning rates to be much lower: 41.9%, 40.9%, 62.1%, and 32.3%. (Kostyshack and Jarrell, 1984, pp. 16-17)

Kostyshack and Jarrell used the overwarning rate in another measure of effectiveness, the ratio of overwarnings to correct warnings. This ratio was calculated by dividing the percentage of cases where adverse weather did not occur by the percentage of cases where adverse weather did occur. The ratios that were reported (before rounding) were .721, 2.846, 8.259, and 24.24 for conditions I, II, III, and IV, respectively. Using this thesis' definition of overwarning, the ratios of overwarnings to correct warnings or Pr(P, W') / Pr(P | W) become: .419, .422, .634, and .521. (Kostyshack and Jarrell, 1984, pp. 16-17)

E. DISCUSSION

The CHARM model takes the cost-loss models of Chapter III a few steps further. This section will comment upon CHARM's assumptions and address some of the merits and drawbacks of the model.

1. Assumptions

a. 30-Knot Winds Interrupt Preparations

If the decision is whether or not to sortie an aircraft carrier, then a lower wind speed should be used as the criterion. The maximum wind speed for moving a carrier is 20 knots (NAVLANTMETOCCEN Norfolk "Hurricane Emily Sortie" brief, 1994). FNMOC's Strike and Wind Probability software can be modified to provide wind probabilities for other than 30 and 50 knots.

b. Losses Occur with the Arrival of 50-Knot Winds

Of course, losses do occur at much lower wind speeds. From January 1969 to July 1994, there were 131 incidents reported Navy-wide of ship damage or personnel injuries caused by "heavy weather" and incurred while the ship was either moored or anchored (Commander, Naval Safety Center Letter, 20 July 1994). Sea state was implicated in the vast majority of the brief narratives. Although "high winds" were mentioned in many of the narratives and could be inferred from others, specific wind speeds were given in only 21 of the 131 incident reports. Winds speeds ranged from 10 kt to "well over 100 kt", with the central tendencies at 40 kt and a standard deviation of 22.2 kt. Most of the incidents occurred during the winter months (outside of hurricane season). Only three of the narratives indicated that the damages were caused by tropical cyclones. The maximum

sustained wind speeds for these storms were 100+ kt, 50 kt, and 65 kt. Considering only this last set, albeit small, 50 knots is a reasonable lower bound.

c. The Fraction of Preparations Completed is $(1 - P_{30})$

This is a legitimate enhancement of the basic cost-loss model and a direct result of the CHARM concept. Preparation costs, then, can be considered time-dependent, by virtue of the fact that the probability of 30-kt winds is an increasing function of time in the domain in which the decision maker is acting, i.e., during the approach of the cyclone.

d. The Fraction of Preparations Completed Will Prevent the Same Fraction, $(1 - P_{30})$, of Avoidable Damage

In other words, if \$2 of protection successfully avoids \$100 in damages, then half that amount of protection will avoid \$50 in damages.

e. The Decision Maker is Risk-Neutral

This implies a linear utility function for costs (see discussion on utilities in Chapter II). It is this assumption that allows us to take straight expected values to find the optimal decision in our "game against nature." There are several reasons why minimizing expected costs may not be a good decision criterion:

1. According to Winkler and Murphy (1985), linear utility is often thought to be a reasonable assumption only when the payoffs (positive or negative) are small (Winkler and Murphy, 1985, p. 507). The costs in this case may be quite large.

2. There is a growing body of research in support of risk-seeking behavior when offered no chance of gain (Slovic et al., 1977; Kunreuther, 1979; Schoemaker and Kunreuther, 1979; Kahneman and Tversky, 1979; MacCrimmon and Wehrung, 1986; and others). This contradicts the risk-aversion for losses espoused by expected utility theory (Von Neumann and Morgenstern, 1947) and prospect theory (Kahneman and Tversky, 1979).

3. Decision makers are probably not computing expected values to choose the optimal course of action. Schoemaker (1979) found that, unless statistically trained, individuals employed additive information-processing strategies, not multiplicative (Schoemaker, 1979, p. 128). Simon (1979) questioned the adequacy of rational choice theory, referring to "the grotesquely powerful intellectual capacities which are supposedly called upon for every choice." (Douglas, 1985, p. 74) Douglas (1985) maintained that people do not consistently make the optimal choice even though there is reason to believe that this is their goal (Douglas, 1985, p. 99). Finally, in a review of empirical studies of behavioral responses to major hazards, Hedge (1987) concluded that a person's behavior was "only loosely connected with any probabilistic risk judgement." (Singleton and Hovden, 1987, p. 151)

4. Decision makers have no incentives for taking risks and would do just as well to employ a conservative nonprobabilistic decision criterion such as the ones described in Chapter II. According to Demsetz, in light of the severe damage that hurricanes can cause "... it seems reasonable to assume that many decision makers prefer to follow a minimax strategy rather than one that seeks to minimize the expected cost." (Demsetz, 1962, p. 10) Lopes (1981) asserted: "... in the real world individuals cannot expect to play any game through the long run of probabilities. Long run arguments should not be applied to decisions about short-run outcomes." (Douglas, 1985, p. 100) Swalm (1971) found that many decision makers preferred not to recommend wise risks to their companies, even though they were aware that their refusal to recommend such action was not in the interests of their

company. The reasoning these businessmen used was ". . . half of the time they would have to explain a $20,000 'mistake,' and if this happened too often they might not be around to share the gains the company would, in the long run, make." (American Society for Engineering Education, 1980, p. 25)

There are also a number of arguments in favor of assuming linear utility for costs:

1. One seldom loses much with a linear model. According to L. J. Savage, "All functions are constant, except for a few that are linear." (American Society for Engineering Education, 1980, p. 125) The same assumption was made by Thompson (1952, 1962), Thompson and Brier (1955), Nelson and Winter (1960), Anderson (1973), Anderson and Burnham (1973), Murphy (1977), and Murphy and Ye (1990).

2. Although utility functions have been derived for individual decision makers (Grayson, 1960), little research has been done on developing a utility curve for an organization.

3. MacCrimmon and Wehrung (1986) reported that, when presented with several important attributes of a risky venture, managers focused most strongly on the average payoff, or expected return (MacCrimmon and Wehrung, 1986, p. 173).

2. The Model

The CHARM model differs from the basic cost-loss ratio model in that the consequence of preparing is not the cost of protection, whether or not adverse weather is experienced. Using the logic of the CHARM concept, the decision maker is faced with the following scenario: **If P_{30} is low**, then nearly all of the preparations will be completed before the arrival of 30-kt winds, therefore the cost of the preparations will be high. These protective

measures, however, will avoid an amount of losses proportional to the amount of preparations completed, therefore the cost of damages will be low. **If P_{30} is high**, then not much time is left for preparations. Granted, the cost of protection will be low, but almost none of the losses will be averted and the cost of damages will be high.

Kostyshack and Jarrell (1984) used the cost matrix in Figure 13 to define their model of the situation described above. However, the matrix and its optimal solution were not included in their published work. Although the rationale for using the cost-benefit ratio as a decision criterion was given in the paper, the connection between the CBR and the curves in the CHARM model was never made. Jerry Jarrell, now the assistant director of the National Hurricane Center, outlined the model in a facsimile sent to this author three days after their interview on 6 June 1994. Further clarifications (telephone conversation between Jerry Jarrell and the author, 16 August 1994) revealed the following insights into the model (refer to Figure 13, p. 77):

a. Given that $0 \leq C \leq L$, the result of protecting when adverse weather occurs, $(1 - P_{30})(C - L)$, is a negative quantity, thus representing a savings. Jarrell called this cell "the money-maker", because it is the only time when the benefits outweigh the costs and the decision maker comes out ahead. In this case, protecting can be considered a wise investment. The costs of making a "wrong" decision (protecting when adverse weather does

not occur or not protecting when adverse weather does occur) are $(1 - P_{30})C$ and L, respectively. These "bad investments" show up as positive quantities or losses in the cost table. The result for (P', W') is zero; the decision maker neither profits nor loses from the decision not to act.

b. The model does not take into account unavoidable damage. The variable L is defined as the cost of the <u>avoidable</u> damage, not the cost of total damages suffered. This sheds some light on the elusive upper left-hand cell. Even if the result $(1 - P_{30})(C - L)$ is a negative cost (and therefore a positive payoff), there may still be negative consequences in the form of unavoidable damages that are not reflected in the payoff. This also explains how the cost incurred when the decision is made to protect is <u>less</u> when adverse weather is experienced than when it is not. By assumption, when less than 50-kt winds are experienced, there is no damage, avoidable or unavoidable.

c. Focusing again on the result in the upper left-hand cell, $(1 - P_{30})(C - L)$, the savings are lower when the probability of 30-kt winds, P_{30}, is high than when P_{30} is low. This result is intuitive and follows from the assumption that $C \leq L$.

d. The model is not defined for all values of P_{30}. The left-hand side of equation 5.3 is meaningless for $P_{30} = 1$. This is not a fatal flaw. The model is no longer needed as a decision aid if $P_{30} = 100\%$; by assumption, the only realistic course of action after the arrival of 30-kt winds is to take

shelter and ride out the storm, actions in keeping with the setting of Condition I (Jarrell and Brand, 1983, p. 1055). At the other endpoint, P_{30} = 0, thus P_{50} = 0 and L = 0. If the decision is to protect (however unlikely), the result is C regardless of whether one uses the expression (1 - P_{30})(C - L) or (1 - P_{30})C. In this case, the decision maker is able to flow between cells of the matrix without encountering inconsistencies. Likewise, if the decision is made to not protect, the cost is zero regardless of whether one looks at the result of (P', W) or (P', W'). A problem arises when C = L, resulting in a zero payoff for (P, W). A zero in the upper left-hand cell for (P, W) does not have the same meaning as a zero in the lower right-hand cell for (P', W'). In the former case, there is the hidden cost of unavoidable damage that is not accounted for by the model, yet is certainly experienced by the decision maker.

3. Other Models

Anderson and Burnham (1973) adapted the basic cost-loss model to include the concept of unavoidable damage. Their "hurricane game box" is shown in Figure 15 where A denotes action taken, A', no action taken, H denotes hurricane, H', no hurricane, C is the cost of protection, L is loss due to hurricane damage and α is the proportion of L that is inevitable, even with protection.

	H	H'
A	$\alpha L + C$	C
A'	L	O

Figure 15. Anderson/Burnham General Model. (after Anderson and Burnham, 1973)

The optimal decision for this scenario is to take action if $P > [C / (1 - \alpha)L]$, where P is the probability of a hurricane striking the area at any given time (the climatological probability). (Anderson and Burnham, 1973, p. 128)

The Anderson/Burnham formulation is appealing in that it is simple, internally consistent and deterministic. C, L and α are constants, all the costs are greater than or equal to zero, and all the losses due to hurricane damage are represented. In this model, the result of taking action when adverse weather occurs is the cost of protection plus the loss that cannot be avoided, whereas in the CHARM model, the result is the cost of preparations completed minus the loss that can be avoided.

Demsetz (1962) also chose an additive approach for computing hurricane costs when preventive measures are taken. He made the point that an increase (decrease) in protective measures will be offset in part by

a decrease (increase) in the costs of damage, so that the sum of protection costs and damage costs will be more stable than either cost by itself. (Demsetz, 1962, p. 10)

Although the inclusion of unavoidable losses in the CHARM model might make it a better representation of reality, it is important to recognize that unavoidable losses are unaffected by the action taken by the decision maker and are, therefore, unnecessary in a prescriptive model like CHARM.

4. Further Considerations

a. Risk

Although the use of a linear model does not take into account the decision maker's attitude toward risk (unless he is indeed risk neutral), the essence of risk is captured by the model in the user-selected confidence level. The 95% confidence level used in the original study (Kostyshack and Jarrell, 1984) is a very risk-averse choice and led to fairly high probabilities of committing type I errors in setting conditions of readiness. It is neither necessary nor recommended to use the same confidence level for all four conditions. The extent of the threat and the cost of the preparations associated with setting the condition should drive the selection of a confidence level. The mission of the organization will also influence the choice. During peacetime, the Navy's overriding concern is to protect the fleet. Contrast this with the plight of a major oil company based in the Gulf

of Mexico which loses approximately $1 million a day if it shuts down operations. The Navy can afford to interrupt business as usual in order to safeguard its ships and therefore, can afford to make decisions with higher levels of confidence. In Jarrell's opinion (telephone conversation between Jerry Jarrell, NHC and the author, 16 August 1994), the oil company might want to select a level around 75% for the evacuation of their oil rigs, whereas the Navy may go as low as 2-5% for setting Condition IV (a "freebie") and as high as 95% for setting Condition I. Although Brand and Blelloch (1975) used 50% as the level of confidence for sortie decisions in the western North Pacific, confidence levels of 70, 80, or 90 percent were discussed as perhaps more reasonable alternatives. (Brand and Blelloch, 1975, p. 358) According to Jarrell, the CHARM model was run using almost every confidence level, however, only the results for 95% were reported.

b. Sequential Decision Making

In a RAND study on the value of weather information, Nelson and Winter (1960) concluded that "storm warnings must be studied within a sequential decision framework" and formally state the general structure of the hurricane protection problem as a guide for future research. As discussed in Chapter I, forecast reliability increases as the forecast period decreases, but if the decision maker waits for more accurate forecasts, he may forgo opportunities for taking protective action or incur the higher cost

of taking such measures in a shorter period of time if the storm continues to threaten. (Nelson and Winter, 1960, pp. 105-106) Murphy and Ye (1990) tackle the formidable problem of implementing a time-dependent version of the cost-loss ratio situation, using exponential models for forecast accuracy and protection costs (Murphy and Ye, 1990, p. 947).

The CHARM model, by design, accommodates the principles of sequential decision making in that it aids decision makers in the setting of readiness conditions. Readiness conditions tailor the response to meet the degree of threat by breaking up the response into four sequential decisions where each decision represents an increasing level of commitment of resources.

c. Model Applications and Refinements

The CHARM model can be applied to the sortie decision by tying the timing of the decision into the setting of readiness conditions. For example, the local destructive weather plan for Norfolk, Virginia links the ship protection activities to the hurricane readiness conditions set by the shore establishment. At **Condition IV**, the following actions are recommended: consider a general personnel recall; coordinate sequence of sortie; publish order/interval of sortie, anchorage assignments and berthing plans for ships remaining in port; publish estimated time of sortie for planning purposes; ships not able to get underway release message to chain

of command; cancel or complete weapons transfers; ships prepare to get underway with at least half ship's power in 24 hours; and disconnect all services to ships. At **Condition III**: if storm movement/strength dictates, issue order to sortie with time of execution; ships prepare to get underway on short notice; ships prepare to sail in heavy seas; and for ships remaining in port, put out additional mooring lines, drop anchors underfoot, and tie down all loose gear. At **Condition II**: unnest ships in port and conduct berthing shifts. At **Condition I**: secure all boating; minimize exposure of personnel to foul weather; issue general damage assessment messages to sortied units to keep them informed about general conditions in the port; and issue return to port order. (COMNAVBASENORVA/SOPA (ADMIN) HAMPINST 3141.1S, 18 May 1993, Enclosure (1), pp. 2-8)

A full sortie out of Norfolk, Virginia requires 36 hours (COMNAVBASENORVA/SOPA(ADMIN) HAMPTONINST 3141.1S, 1993). In order to complete preparations prior to the arrival of 30-kt winds, the decision to sortie must be made soon after the setting of Condition III and executed before the setting of Condition II. In some cases, the sortie decision may coincide with the National Hurricane Center's issuance of a Hurricane Watch which occurs approximately 36 hours before landfall. (Turpin and Brand, 1982, p. I-12) Allowances should be made for the inevitable delays from recommendation to decision to action.

The Navy's wind probability model presumes that the winds are over water, not land. For harbors such as Guantanamo Bay, Cuba where the terrain provides substantial shelter from destructive winds, wind probabilities will be overestimated and cause a bias in the CHARM model results. (Kostyshack and Jarrell, 1984, p. 22) Jarrell (1982) describes a method for adjusting wind probabilities for terrain influence. These adjusted probabilities should be developed and used to produce more accurate readiness condition thresholds for those bases where terrain is a factor (Jarrell, 1982, p. 14).

Chapter VI discusses Atlantic tropical cyclone forecast errors as well as the accuracy of probability forecasts.

VI. TROPICAL CYCLONE FORECAST ERRORS

A. TROPICAL CYCLONE FORECASTING

Despite technological advances, tropical cyclone forecasting remains a subjective process that is heavily reliant on forecaster skill and experience. Although aircraft reconnaissance, radar, buoys and satellites have improved the detection and monitoring of tropical cyclones, they cannot provide the three-dimensional data required for hurricane track forecasting. Computer models often predict very different tracks for the same storm. It is important that decision makers be made aware of the current limitations in forecast accuracy. (American Meteorological Society, 1993, p. 1379)

B. ATLANTIC TROPICAL CYCLONE FORECAST ERRORS

Forecasters are better at predicting some characteristics of the hurricane than others. Using a combination of climatology and persistence as a basis for comparison, the following is the order of skill for forecast elements (highest skill first): track (or path) forecast, translation speed forecast, maximum winds forecast and size forecast. The first two elements are nearly equal in skill, with only a slight preference for track. There is a sizeable gap between the skill associated with track and speed forecasts and the skill in forecasting maximum winds. A comparable gap separates winds and size. Track forecast skill has been shown to exist out to 72 hours, with

the 48-hour forecast showing the highest level of skill. (American Meteorological Society, 1993, p. 1379)

The degree of difficulty in accurately forecasting hurricanes is manifest in the errors associated with the forecasts. The average official NHC tropical cyclone track forecast errors for the decade 1982-1991 were 54, 104, 206, and 309 n mi for the 12-, 24-, 48-, and 72-h forecasts, respectively (Lawrence and Gross, 1993). The average official NHC tropical cyclone maximum wind speed forecast errors for 1982-1991 were 8.0, 11.5, 16.0, and 19.5 kt for the 12-, 24-, 48-, and 72-h forecasts, respectively. (Minutes of the 47th Interdepartmental Hurricane Conference, 23-26 February 1993, p. B-16) According to the American Meteorological Society's policy statement on hurricane detection, tracking and forecasting,

> these [average wind speed] errors are deceptively low, however, since they are heavily weighted toward the average condition where intensity changes are gradual and persistence forecasts work well. They do not reflect the occasional large misses that can occur with rapid strengthening or weakening of a storm. (American Meteorological Society, 1993, p. 1379)

Appleman (1962) recognized that the forecast error values in the Atlantic-Caribbean area had a latitudinal variation similar to that in the Pacific, with smaller errors in the south and larger in the north (Appleman, 1962, p. 4). Neumann and Pelissier (1981) found that the Atlantic tropical cyclone forecast errors for 1970-1979 were correlated with the initial latitude of the storm. Excessive errors were mainly confined to the region north of

24.5 degrees N. These errors typically arose in situations where the storm was forecast to recurve and did not, or was forecast to not recurve and did. (Neumann and Pelissier, 1981, pp. 1248-1249) Figure 16 shows the geographical variation in the average 48-hour tropical cyclone forecast error. (Neumann and Pelissier, 1981, p. 1262) The American Meteorological Society reported that the track forecast errors were up to 30% greater than the mean in the central Atlantic region, and up to 30% less than the mean in the Gulf of Mexico and the Caribbean. These variations were attributed to different characteristics of hurricane motion in the southern regions as well as better meteorological data availability due to the greater number of observation sites in the Gulf of Mexico and the Caribbean. (American Meteorological Society, 1993, p. 1379)

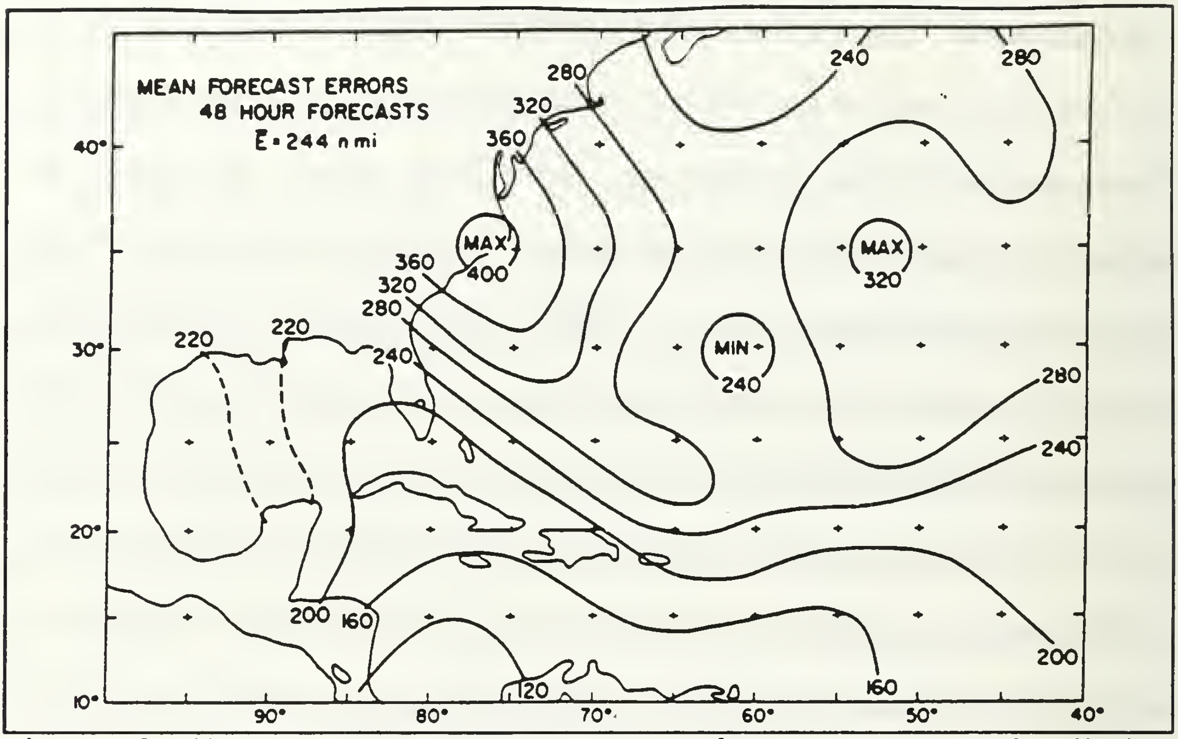

Figure 16. 48-Hour Mean Forecast Errors. (from Neumann and Pelissier, 1981)

A north-south dichotomy can also be seen in landfall forecast errors, that is, errors in the prediction of the point where a hurricane is expected to cross a coastline. Neumann and Pelissier (1981) explained:

> The magnitude of the landfall error is sensitive to the orientation of the storm track relative to the segment of coastline the storm approaches. If a storm approaches normal to a coastline, a small directional forecast error results in a small landfall error, whereas, if the angle of approach is small, a small directional error can result in a large landfall error .... the former situation usually occurs around the Gulf of Mexico, and the latter frequently prevails along the Atlantic Coast. (Neumann and Pelissier, 1981, p. 1264)

The average landfall error for 1970-1979 was only 39 n mi, with a median of 31.5 n mi. (Neumann and Pelissier, 1981, p. 1264)

C. IMPROVEMENTS IN FORECASTING

Neumann and Pelissier (1981) suggested that the ability to forecast hurricane motion had been on a plateau since about 1970.(Neumann and Pelissier, 1981, p. 1265) The belief that no appreciable improvements have been made in forecasting in quite some time is still held by some. (Interview between Charlie Mauck, FNMOC, Monterey and the author, 13 May 1994) A recent study showed this is not the case. McAdie and Lawrence (1993) analyzed the official NHC tropical cyclone track forecast errors in the Atlantic basin from 1970-1991. After adjusting for forecast difficulty, they found that the errors decreased by an average of .7% per year at 24 hours, by 1.0% per year for the 48-hour forecast, and by 1.2% per year for the 72-hour forecast, indicating a significant long-term downward trend. In other words, the 24-, 48-, and 72-hour track forecast errors have declined 14%, 20%, and 24%, respectively, over the past 20 years. (Minutes of the 47th Interdepartmental Hurricane Conference, 23-26 February 1993, p. A-77)

Improvements of this magnitude could translate into considerable savings to the U.S. Navy. Recall from Chapter III that Brand and Blelloch (1975) estimated that a 20% improvement in the 48-hour forecast error would mean an annual savings of $292,500 in 1975 dollars for eight western North Pacific installations. Based on this estimate, the potential savings to

the sampled bases in 1993 dollars from the 20% decrease in the 48-hour forecast error reported by McAdie and Lawrence (1993) is $785,618.[28]

Additional improvements in forecast errors may be forthcoming. Prior to 1992, NHC classified a forecast into one of three categories based on its degree of difficulty: "hard", "easy," and "all others" (Interview between Jerry Jarrell, NHC and the author, 6 June 1994). Within each category, the forecast errors were assumed to follow a bivariate normal distribution with known mean, standard deviation, and correlation coefficient for each class (Kostyshack and Jarrell, 1984, p. 6). Today, NHC uses 40 past forecasts, matched by year, month, latitude and longitude, to derive a distribution for the current forecast. According to Jarrell, the result is a flatter, wider distribution that produces greater discrimination and higher probabilities (Interview between Jerry Jarrell, NHC and the author, 6 June 1994).

The U.S. Navy Strike and Wind Probability Forecast software relies on forecast errors to derive probability forecasts. Unfortunately, the forecast errors have not been updated since the program's inception 17 years ago (Interview between Charlie Mauck, FNMOC, Monterey and the author, 13 May 1994). Consequently, the probability forecasts do not reflect the improvements in the official NHC forecasts over the past two decades. In

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[28]The U.S. City Average All Items Consumer Price Index (CPI) for all urban consumers for 1975 is 53.8 and for 1993 is 144.5 (U.S. Bureau of Labor and Statistics, Washington, D.C., 7 September 1994. Telephone (202) 606-7000). To convert to 1993 dollars: 144.5/53.8 = 2.6859 (multiplication factor applied to 1975 dollar amounts).

light of the savings shown by Brand and Blelloch (1975), a modification in the software is indicated.

VII. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

This thesis analyzed one aspect of the "hurricane problem" within the framework of the cost-loss ratio situation. The question of whether or not to sortie U.S. Navy ships to avoid a hurricane threat was explored using decision analysis. Particular attention was given to the use of probability forecasting in decision making. Reducing the number of unnecessary sorties without putting the fleet at significantly increased risk was identified as a goal. Analysis included interviews with several prominent tropical cyclone experts, an exhaustive literature review and a critique of the available hurricane decision aids.

A number of conclusions can be drawn from this study:

1. The long lead time needed to complete a full sortie requires the decision maker to rely on forecasts that may contain large errors.

2. Although the cost-loss ratio is a useful criterion for hurricane sortie decisions, the huge variations in the costs associated with hurricane preparations and avoidable damages make the cost-loss ratio a difficult quantity to estimate directly.

3. Forecasts used in conjunction with the port studies in the Hurricane Havens Handbook for the North Atlantic Ocean and local destructive weather instructions provide the Navy decision maker with the data needed to make an informed decision; however, he may have difficulty integrating all of the information without the assistance of a decision aid. There are a number of excellent commercial hurricane decision aids (i.e., GDS and CHARM) that can help the decision maker visualize and quickly assess the threat.

4. The ability to incorporate probability forecasts into the analysis is essential. The wind probability forecast is especially useful in that it simultaneously accounts for the errors in all aspects of the hurricane threat.

5. The cost-loss based CHARM model is a simple, reliable tool that can be applied to preparation decisions regarding ship sorties and the setting of hurricane readiness conditions.

6. The National Hurricane Center official track forecast errors have been steadily decreasing over the past twenty years.

B. RECOMMENDATIONS

Based on these findings and the research conducted, the following recommendations are made:

1. The CHARM methodology described in Kostyshack and Jarrell (1984) should be used to develop CHARM nomographs for harbors used by the U.S. Navy fleet. NHC's current method for estimating forecast errors should be used to generate the simulated forecasts. CHARM nomographs should be included in the <u>Hurricane Havens Handbook</u> port studies.

2. The U.S. Navy Strike and Wind Probability software should be updated to reflect the current NHC official forecast errors. Terrain adjustments should be applied to the wind probabilities where needed. The National Hurricane Center is willing to provide FNMOC with any assistance necessary. (Interview between Jerry Jarrell, NHC and the author, 6 June 1994)

3. Probability forecasts should be incorporated into ATCFjr.

4. Navy decision makers and forecasters should use Shiftrack from GDS Toolkit to practice responding to hurricane threats. Shiftrack should also be used to train Base Hurricane Preparedness Officers.

5. A concerted effort should be made to educate Navy decision makers regarding the proper interpretation and use of probability forecasts.

C. FUTURE RESEARCH

Several areas for future research are identified. In the past, inadequate tropical cyclone record-keeping by hurricane preparedness officers prevented a number of researchers from successfully "backcasting" the readiness conditions set at sampled installations. Automated hurricane tracking programs in use today may improve the local tropical cyclone archives and allow for a more precise accounting of overwarning rates.

At the 48th Interdepartmental Hurricane Conference, the NAVLANTMETOCCEN Norfolk requested in their Hurricane Emily Sortie brief that the NHC extend their forecasts out to 96 hours. Ship routing often requires forecasting for more than three days. The NHC track forecasts currently show skill out to 72 hours; beyond that, climatology is the only objective guidance available. The global forecast models at FNMOC and other centers now produce track forecasts out to 120 hours once the storm has reached 35-kt intensity. Although many of these forecasts cannot be verified because the storm does not persist for another five days, limited statistics suggest some skill for many "well-behaved" storms. Continued research in the area of longer-range tropical cyclone forecasting would be beneficial.

Once a CHARM nomograph for Norfolk, Virginia has been developed, the CHARM model should be applied to the Norfolk case study on the Hurricane Emily Sortie. This was an extremely difficult determination for Navy decision makers because the storm came so close to Norfolk before turning away. Also, sensitivity analysis of the CHARM model results should be conducted in order to see how the cost-benefit ratio and type I and type II errors are affected when different confidence levels are used.

Future study should be devoted to improving the sortie process. Possible research questions might be "Where are the bottlenecks?" and "How much effect will an additional tug have on the time needed to sortie?" The shorter the required lead time, the more accurate the forecasts will be.

One aspect of hurricane threat assessment that the decision aids (except for the local destructive weather instruction) did not factor into their analysis was the timing of decisions with regard to the number of daylight hours remaining. For example, it does little good to issue a warning, set the next higher condition of readiness, or order a sortie after everyone has retired for the night. A night sortie is highly undesirable; darkness adds to the difficulty of the sortie and greatly increases the possibility of ships colliding (Minutes of the 47th Interdepartmental Hurricane Conference, 23-26 February 1993, p. B-81).

Finally, an in-depth analysis of tropical cyclone size (wind distribution) forecast errors similar to Neumann and Pelissier (1981) is

needed. Currently, only track and maximum wind speed forecast errors are published. Although it is commonly assumed that an intensity (maximum wind speed) increase will be accompanied by a size increase, recent research indicates that this assumption does not always hold. Identification of statistically significant biases or trends in the official forecasts is the first step toward improving the skill associated with wind distribution forecasts.

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